

Topics in Inequalities - Theorems and Techniques

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Introduction

Inequalities are useful in all fields of Mathematics. The aim of this *problem-oriented* book is to present elementary techniques in the theory of inequalities. The readers will meet classical theorems including *Schur's inequality*, *Muirhead's theorem*, *the Cauchy-Schwarz inequality*, *the Power Mean inequality*, *the AM-GM inequality*, and *Hölder's theorem*. I would greatly appreciate hearing about comments and corrections from my readers. You can send email to me at **ultrametric@gmail.com**

To Students

My target readers are challenging high schools students and undergraduate students. The given techniques in this book are just the tip of the inequalities iceberg. Young students should find their own methods to attack various problems. A great Hungarian Mathematician Paul Erdős was fond of saying that *God has a transfinite book with all the theorems and their best proofs*. I strongly encourage readers to send me their own creative solutions of the problems in this book. **Have fun!**

Acknowledgement

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Resources on the Web

1. *MathLinks*, <http://www.mathlinks.ro>
2. *Art of Problem Solving*, <http://www.artofproblemsolving.com>
3. *MathPro Press*, <http://www.mathpropress.com>
4. K. S. Kedlaya, *A < B*, <http://www.unl.edu/amc/a-activities/a4-for-students/s-index.html>
5. T. J. Mildorf, *Olympiad Inequalities*, <http://web.mit.edu/tmildorf/www>

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Chapter 1

Geometric Inequalities

It gives me the same pleasure when someone else proves a good theorem as when I do it myself. E. Landau

1.1 Ravi Substitution

Many inequalities are simplified by some suitable substitutions. We begin with a classical inequality in triangle geometry. What is the first¹ *nontrivial* geometric inequality ? In 1746, Chapple showed that

Theorem 1.1.1. (Chapple 1746, Euler 1765) *Let R and r denote the radii of the circumcircle and incircle of the triangle ABC . Then, we have $R \geq 2r$ and the equality holds if and only if ABC is equilateral.*

Proof. Let $BC = a$, $CA = b$, $AB = c$, $s = \frac{a+b+c}{2}$ and $S = [ABC]$.² Recall the well-known identities : $S = \frac{abc}{4R}$, $S = rs$, $S^2 = s(s-a)(s-b)(s-c)$. Hence, $R \geq 2r$ is equivalent to $\frac{abc}{4S} \geq 2\frac{S}{s}$ or $abc \geq 8\frac{S^2}{s}$ or $abc \geq 8(s-a)(s-b)(s-c)$. We need to prove the following. \square

Theorem 1.1.2. ([AP], A. Padoa) *Let a , b , c be the lengths of a triangle. Then, we have*

$$abc \geq 8(s-a)(s-b)(s-c) \text{ or } abc \geq (b+c-a)(c+a-b)(a+b-c)$$

and the equality holds if and only if $a = b = c$.

First Proof. We use the Ravi Substitution : Since a , b , c are the lengths of a triangle, there are positive reals x , y , z such that $a = y+z$, $b = z+x$, $c = x+y$. (Why?) Then, the inequality is $(y+z)(z+x)(x+y) \geq 8xyz$ for $x, y, z > 0$. However, we get $(y+z)(z+x)(x+y) - 8xyz = x(y-z)^2 + y(z-x)^2 + z(x-y)^2 \geq 0$. \square

Exercise 1. *Let ABC be a right triangle. Show that $R \geq (1 + \sqrt{2})r$. When does the equality hold ?*

It's natural to ask that the inequality in the theorem 2 holds for arbitrary positive reals a , b , c ? Yes ! It's possible to prove the inequality without the additional condition that a , b , c are the lengths of a triangle :

Theorem 1.1.3. *Let $x, y, z > 0$. Then, we have $xyz \geq (y+z-x)(z+x-y)(x+y-z)$. The equality holds if and only if $x = y = z$.*

Proof. Since the inequality is symmetric in the variables, without loss of generality, we may assume that $x \geq y \geq z$. Then, we have $x+y > z$ and $z+x > y$. If $y+z > x$, then x, y, z are the lengths of the sides of a triangle. In this case, by the theorem 2, we get the result. Now, we may assume that $y+z \leq x$. Then, $xyz > 0 \geq (y+z-x)(z+x-y)(x+y-z)$. \square

The inequality in the theorem 2 holds when some of x, y, z are zeros :

Theorem 1.1.4. *Let $x, y, z \geq 0$. Then, we have $xyz \geq (y+z-x)(z+x-y)(x+y-z)$.*

¹The first geometric inequality is the Triangle Inequality : $AB + BC \geq AC$

²In this book, $[P]$ stands for the area of the polygon P .

Proof. Since $x, y, z \geq 0$, we can find *positive* sequences $\{x_n\}, \{y_n\}, \{z_n\}$ for which

$$\lim_{n \rightarrow \infty} x_n = x, \lim_{n \rightarrow \infty} y_n = y, \lim_{n \rightarrow \infty} z_n = z.$$

Applying the theorem 2 yields

$$x_n y_n z_n \geq (y_n + z_n - x_n)(z_n + x_n - y_n)(x_n + y_n - z_n).$$

Now, taking the limits to both sides, we get the result. □

Clearly, the equality holds when $x = y = z$. However, $xyz = (y+z-x)(z+x-y)(x+y-z)$ and $x, y, z \geq 0$ does not guarantee that $x = y = z$. In fact, for $x, y, z \geq 0$, the equality $xyz = (y+z-x)(z+x-y)(x+y-z)$ is equivalent to

$$x = y = z \text{ or } x = y, z = 0 \text{ or } y = z, x = 0 \text{ or } z = x, y = 0.$$

It's straightforward to verify the equality

$$xyz - (y+z-x)(z+x-y)(x+y-z) = x(x-y)(x-z) + y(y-z)(y-x) + z(z-x)(z-y).$$

Hence, the theorem 4 is a particular case of Schur's inequality.

Problem 1. (IMO 2000/2, Proposed by Titu Andreescu) Let a, b, c be positive numbers such that $abc = 1$. Prove that

$$\left(a - 1 + \frac{1}{b}\right) \left(b - 1 + \frac{1}{c}\right) \left(c - 1 + \frac{1}{a}\right) \leq 1.$$

First Solution. Since $abc = 1$, we make the substitution $a = \frac{x}{y}$, $b = \frac{y}{z}$, $c = \frac{z}{x}$ for $x, y, z > 0$.³ We rewrite the given inequality in the terms of x, y, z :

$$\left(\frac{x}{y} - 1 + \frac{z}{y}\right) \left(\frac{y}{z} - 1 + \frac{x}{z}\right) \left(\frac{z}{x} - 1 + \frac{y}{x}\right) \leq 1 \Leftrightarrow xyz \geq (y+z-x)(z+x-y)(x+y-z).$$

□

The *Ravi Substitution* is useful for inequalities for the lengths a, b, c of a triangle. After the *Ravi Substitution*, we can remove the condition that they are the lengths of the sides of a triangle.

Problem 2. (IMO 1983/6) Let a, b, c be the lengths of the sides of a triangle. Prove that

$$a^2b(a-b) + b^2c(b-c) + c^2a(c-a) \geq 0.$$

First Solution. After setting $a = y+z$, $b = z+x$, $c = x+y$ for $x, y, z > 0$, it becomes

$$x^3z + y^3x + z^3y \geq x^2yz + xy^2z + xyz^2 \text{ or } \frac{x^2}{y} + \frac{y^2}{z} + \frac{z^2}{x} \geq x + y + z,$$

which follows from the Cauchy-Schwarz inequality

$$(y+z+x) \left(\frac{x^2}{y} + \frac{y^2}{z} + \frac{z^2}{x}\right) \geq (x+y+z)^2.$$

□

Exercise 2. Let a, b, c be the lengths of a triangle. Show that

$$\frac{a}{b+c} + \frac{b}{c+a} + \frac{c}{a+b} < 2.$$

Exercise 3. (Darij Grinberg) Let a, b, c be the lengths of a triangle. Show the inequalities

$$a^3 + b^3 + c^3 + 3abc - 2b^2a - 2c^2b - 2a^2c \geq 0,$$

and

$$3a^2b + 3b^2c + 3c^2a - 3abc - 2b^2a - 2c^2b - 2a^2c \geq 0.$$

³For example, take $x = 1$, $y = \frac{1}{a}$, $z = \frac{1}{ab}$.

1.2 Weitzenböck's inequality

In this section, we discuss Weitzenböck's inequality and related inequalities.

Problem 3. (IMO 1961/2, Weitzenböck's inequality) Let a, b, c be the lengths of a triangle with area S . Show that

$$a^2 + b^2 + c^2 \geq 4\sqrt{3}S.$$

Solution. Write $a = y + z$, $b = z + x$, $c = x + y$ for $x, y, z > 0$. It's equivalent to

$$(y+z)^2 + (z+x)^2 + (x+y)^2 \geq 48(x+y+z)xyz,$$

which can be obtained as following :

$$(y+z)^2 + (z+x)^2 + (x+y)^2 \geq 16(yz + zx + xy)^2 \geq 16 \cdot 3(xy \cdot yz + yz \cdot zx + xy \cdot yz).$$

Here, we used the well-known inequalities $p^2 + q^2 \geq 2pq$ and $(p+q+r)^2 \geq 3(pq + qr + rp)$. \square

Theorem 1.2.1. (Hadwiger-Finsler inequality) For any triangle ABC with sides a, b, c and area F , the following inequality holds.

$$2ab + 2bc + 2ca - (a^2 + b^2 + c^2) \geq 4\sqrt{3}F.$$

First Proof. After the substitution $a = y + z$, $b = z + x$, $c = x + y$, where $x, y, z > 0$, it becomes

$$xy + yz + zx \geq \sqrt{3xyz(x+y+z)},$$

which follows from the identity

$$(xy + yz + zx)^2 - 3xyz(x+y+z) = \frac{(xy - yz)^2 + (yz - zx)^2 + (zx - xy)^2}{2}.$$

\square

Second Proof. We give a convexity proof. There are various ways to deduce the following identity:

$$\frac{2ab + 2bc + 2ca - (a^2 + b^2 + c^2)}{4F} = \tan \frac{A}{2} + \tan \frac{B}{2} + \tan \frac{C}{2}.$$

Since $\tan x$ is convex on $(0, \frac{\pi}{2})$, Jensen's inequality shows that

$$\frac{2ab + 2bc + 2ca - (a^2 + b^2 + c^2)}{4F} \geq 3 \tan \left(\frac{\frac{A}{2} + \frac{B}{2} + \frac{C}{2}}{3} \right) = \sqrt{3}.$$

\square

Tsintsifas proved a simultaneous generalization of Weitzenböck's inequality and Nesbitt's inequality.

Theorem 1.2.2. (Tsintsifas) Let p, q, r be positive real numbers and let a, b, c denote the sides of a triangle with area F . Then, we have

$$\frac{p}{q+r}a^2 + \frac{q}{r+p}b^2 + \frac{r}{p+q}c^2 \geq 2\sqrt{3}F.$$

Proof. (V. Pambuccian) By Hadwiger-Finsler inequality, it suffices to show that

$$\frac{p}{q+r}a^2 + \frac{q}{r+p}b^2 + \frac{r}{p+q}c^2 \geq \frac{1}{2}(a+b+c)^2 - (a^2 + b^2 + c^2)$$

or

$$\left(\frac{p+q+r}{q+r} \right) a^2 + \left(\frac{p+q+r}{r+p} \right) b^2 + \left(\frac{p+q+r}{p+q} \right) c^2 \geq \frac{1}{2}(a+b+c)^2$$

or

$$((q+r) + (r+p) + (p+q)) \left(\frac{1}{q+r}a^2 + \frac{1}{r+p}b^2 + \frac{1}{p+q}c^2 \right) \geq (a+b+c)^2.$$

However, this is a straightforward consequence of the Cauchy-Schwarz inequality. \square

Theorem 1.2.3. (Neuberg-Pedoe inequality) Let a_1, b_1, c_1 denote the sides of the triangle $A_1B_1C_1$ with area F_1 . Let a_2, b_2, c_2 denote the sides of the triangle $A_2B_2C_2$ with area F_2 . Then, we have

$$a_1^2(b_2^2 + c_2^2 - a_2^2) + b_1^2(c_2^2 + a_2^2 - b_2^2) + c_1^2(a_2^2 + b_2^2 - c_2^2) \geq 16F_1F_2.$$

Notice that it's a generalization of Weitzenböck's inequality.(Why?) In [GC], G. Chang proved Neuberg-Pedoe inequality by using complex numbers. For very interesting geometric observations and proofs of Neuberg-Pedoe inequality, see [DP] or [GI, pp.92-93]. Here, we offer three algebraic proofs.

Lemma 1.2.1.

$$a_1^2(a_2^2 + b_2^2 - c_2^2) + b_1^2(b_2^2 + c_2^2 - a_2^2) + c_1^2(c_2^2 + a_2^2 - b_2^2) > 0.$$

Proof. Observe that it's equivalent to

$$(a_1^2 + b_1^2 + c_1^2)(a_2^2 + b_2^2 + c_2^2) > 2(a_1^2a_2^2 + b_1^2b_2^2 + c_1^2c_2^2).$$

From Heron's formula, we find that, for $i = 1, 2$,

$$16F_i^2 = (a_i^2 + b_i^2 + c_i^2)^2 - 2(a_i^4 + b_i^4 + c_i^4) > 0 \quad \text{or} \quad a_i^2 + b_i^2 + c_i^2 > \sqrt{2(a_i^4 + b_i^4 + c_i^4)}.$$

The Cauchy-Schwarz inequality implies that

$$(a_1^2 + b_1^2 + c_1^2)(a_2^2 + b_2^2 + c_2^2) > 2\sqrt{(a_1^4 + b_1^4 + c_1^4)(a_2^4 + b_2^4 + c_2^4)} \geq 2(a_1^2a_2^2 + b_1^2b_2^2 + c_1^2c_2^2).$$

□

First Proof. ([LC1], Carlitz) By the lemma, we obtain

$$L = a_1^2(b_2^2 + c_2^2 - a_2^2) + b_1^2(c_2^2 + a_2^2 - b_2^2) + c_1^2(a_2^2 + b_2^2 - c_2^2) > 0,$$

Hence, we need to show that

$$L^2 - (16F_1^2)(16F_2^2) \geq 0.$$

One may easily check the following identity

$$L^2 - (16F_1^2)(16F_2^2) = -4(UV + VW + WU),$$

where

$$U = b_1^2c_2^2 - b_2^2c_1^2, \quad V = c_1^2a_2^2 - c_2^2a_1^2 \quad \text{and} \quad W = a_1^2b_2^2 - a_2^2b_1^2.$$

Using the identity

$$a_1^2U + b_1^2V + c_1^2W = 0 \quad \text{or} \quad W = -\frac{a_1^2}{c_1^2}U - \frac{b_1^2}{c_1^2}V,$$

one may also deduce that

$$UV + VW + WU = -\frac{a_1^2}{c_1^2} \left(U - \frac{c_1^2 - a_1^2 - b_1^2}{2a_1^2}V \right)^2 - \frac{4a_1^2b_1^2 - (c_1^2 - a_1^2 - b_1^2)^2}{4a_1^2c_1^2}V^2.$$

It follows that

$$UV + VW + WU = -\frac{a_1^2}{c_1^2} \left(U - \frac{c_1^2 - a_1^2 - b_1^2}{2a_1^2}V \right)^2 - \frac{16F_1^2}{4a_1^2c_1^2}V^2 \leq 0.$$

□

Carlitz also observed that the Neuberg-Pedoe inequality can be deduced from Aczél's inequality.

Theorem 1.2.4. (Aczél's inequality) Let $a_1, \dots, a_n, b_1, \dots, b_n$ be positive real numbers satisfying

$$a_1^2 \geq a_2^2 + \dots + a_n^2 \text{ and } b_1^2 \geq b_2^2 + \dots + b_n^2.$$

Then, the following inequality holds.

$$a_1 b_1 - (a_2 b_2 + \dots + a_n b_n) \geq \sqrt{(a_1^2 - (a_2^2 + \dots + a_n^2)) (b_1^2 - (b_2^2 + \dots + b_n^2))}$$

Proof. ([AI]) The Cauchy-Schwarz inequality shows that

$$a_1 b_1 \geq \sqrt{(a_2^2 + \dots + a_n^2)(b_2^2 + \dots + b_n^2)} \geq a_2 b_2 + \dots + a_n b_n.$$

Then, the above inequality is equivalent to

$$(a_1 b_1 - (a_2 b_2 + \dots + a_n b_n))^2 \geq (a_1^2 - (a_2^2 + \dots + a_n^2)) (b_1^2 - (b_2^2 + \dots + b_n^2)).$$

In case $a_1^2 - (a_2^2 + \dots + a_n^2) = 0$, it's trivial. Hence, we now assume that $a_1^2 - (a_2^2 + \dots + a_n^2) > 0$. The main trick is to think of the following quadratic polynomial

$$P(x) = (a_1 x - b_1)^2 - \sum_{i=2}^n (a_i x - b_i)^2 = \left(a_1^2 - \sum_{i=2}^n a_i^2 \right) x^2 + 2 \left(a_1 b_1 - \sum_{i=2}^n a_i b_i \right) x + \left(b_1^2 - \sum_{i=2}^n b_i^2 \right).$$

Since $P\left(\frac{b_1}{a_1}\right) = -\sum_{i=2}^n \left(a_i \left(\frac{b_1}{a_1} \right) - b_i \right)^2 \leq 0$ and since the coefficient of x^2 in the quadratic polynomial P is positive, P should have at least one real root. Therefore, P has nonnegative discriminant. It follows that

$$\left(2 \left(a_1 b_1 - \sum_{i=2}^n a_i b_i \right) \right)^2 - 4 \left(a_1^2 - \sum_{i=2}^n a_i^2 \right) \left(b_1^2 - \sum_{i=2}^n b_i^2 \right) \geq 0.$$

□

Second Proof of Neuberg-Pedoe inequality. ([LC2], Carlitz) We rewrite it in terms of $a_1, b_1, c_1, a_2, b_2, c_2$:

$$\begin{aligned} & (a_1^2 + b_1^2 + c_1^2)(a_2^2 + b_2^2 + c_2^2) - 2(a_1^2 a_2^2 + b_1^2 b_2^2 + c_1^2 c_2^2) \\ & \geq \sqrt{\left((a_1^2 + b_1^2 + c_1^2)^2 - 2(a_1^4 + b_1^4 + c_1^4) \right) \left((a_2^2 + b_2^2 + c_2^2)^2 - 2(a_2^4 + b_2^4 + c_2^4) \right)}. \end{aligned}$$

We employ the following substitutions

$$x_1 = a_1^2 + b_1^2 + c_1^2, x_2 = \sqrt{2} a_1^2, x_3 = \sqrt{2} b_1^2, x_4 = \sqrt{2} c_1^2,$$

$$y_1 = a_2^2 + b_2^2 + c_2^2, y_2 = \sqrt{2} a_2^2, y_3 = \sqrt{2} b_2^2, y_4 = \sqrt{2} c_2^2.$$

As in the proof of the lemma 5, we find that

$$x_1^2 > x_2^2 + y_3^2 + x_4^2 \text{ and } y_1^2 > y_2^2 + y_3^2 + y_4^2.$$

We now apply Aczél's inequality to get the inequality

$$x_1 y_1 - x_2 y_2 - x_3 y_3 - x_4 y_4 \geq \sqrt{(x_1^2 - (x_2^2 + y_3^2 + x_4^2)) (y_1^2 - (y_2^2 + y_3^2 + y_4^2))}.$$

□

We close this section with a very simple proof by a former student in KMO⁴ summer program.

⁴Korean Mathematical Olympiads

Third Proof. Toss two triangles $\triangle A_1B_1C_1$ and $\triangle A_2B_2C_2$ on \mathbb{R}^2 :

$$A_1(0, p_1), B_1(p_2, 0), C_1(p_3, 0), A_2(0, q_1), B_2(q_2, 0), \text{ and } C_2(q_3, 0).$$

It therefore follows from the inequality $x^2 + y^2 \geq 2|xy|$ that

$$\begin{aligned} & a_1^2(b_2^2 + c_2^2 - a_2^2) + b_1^2(c_2^2 + a_2^2 - b_2^2) + c_1^2(a_2^2 + b_2^2 - c_2^2) \\ &= (p_3 - p_2)^2(2q_1^2 + 2q_1q_2) + (p_1^2 + p_3^2)(2q_2^2 - 2q_2q_3) + (p_1^2 + p_2^2)(2q_3^2 - 2q_2q_3) \\ &= 2(p_3 - p_2)^2q_1^2 + 2(q_3 - q_2)^2p_1^2 + 2(p_3q_2 - p_2q_3)^2 \\ &\geq 2((p_3 - p_2)q_1)^2 + 2((q_3 - q_2)p_1)^2 \\ &\geq 4|(p_3 - p_2)q_1| \cdot |(q_3 - q_2)p_1| \\ &= 16F_1F_2. \end{aligned}$$

□

1.3 Erdös-Mordell Theorem

In this section, we discuss famous Erdös-Mordell Theorem and related inequalities.

Theorem 1.3.1. (Erdös-Mordell Theorem) *If from a point P inside a given triangle ABC perpendiculars PH_1, PH_2, PH_3 are drawn to its sides, then $PA + PB + PC \geq 2(PH_1 + PH_2 + PH_3)$.*

This was conjectured by Paul Erdös in 1935, and first proved by Mordell in the same year. Several proofs of this inequality have been given, using Ptolemy's theorem by André Avez, angular computations with similar triangles by Leon Bankoff, area inequality by V. Komornik, or using trigonometry by Mordell and Barrow.

Proof. ([MB], Mordell) Let $d_1 = PA, d_2 = PB, d_3 = PC, h_1 = PH_1, h_2 = PH_2$ and $h_3 = PH_3$. We apply the Cosine Law to obtain

$$\overline{H_2 H_3}^2 = h_2^2 + h_3^2 - 2h_2 h_3 \cos(\pi - A) = h_2^2 + h_3^2 - 2h_2 h_3 \cos(B + C).$$

It follows that

$$\overline{H_2 H_3}^2 = (h_2 \sin C + h_3 \sin B)^2 + (h_2 \cos C - h_3 \cos B)^2$$

so that

$$\overline{H_2 H_3} \geq h_2 \sin C + h_3 \sin B.$$

Since $\overline{H_2 H_3} = d_1 \sin A$, this implies that

$$d_1 \geq \left(\frac{\sin C}{\sin A} \right) h_2 + \left(\frac{\sin B}{\sin A} \right) h_3.$$

By the same reasoning, we obtain

$$d_2 \geq \left(\frac{\sin A}{\sin B} \right) h_3 + \left(\frac{\sin C}{\sin B} \right) h_1 \quad \text{and} \quad d_3 \geq \left(\frac{\sin B}{\sin C} \right) h_1 + \left(\frac{\sin A}{\sin C} \right) h_2.$$

Adding these three inequalities, we obtain

$$d_1 + d_2 + d_3 \geq \left(\frac{\sin B}{\sin C} + \frac{\sin C}{\sin B} \right) h_1 + \left(\frac{\sin C}{\sin A} + \frac{\sin A}{\sin C} \right) h_2 + \left(\frac{\sin A}{\sin B} + \frac{\sin B}{\sin A} \right) h_3.$$

The AM-GM inequality guarantees that $d_1 + d_2 + d_3 \geq 2h_1 + 2h_2 + 2h_3$. □

We need a trigonometric inequality to establish a stronger result by D. F. Barrow.

Proposition 1.3.1. *Let $x, y, z, \theta_1, \theta_2, \theta_3$ be real numbers with $\theta_1 + \theta_2 + \theta_3 = \pi$. Then,*

$$x^2 + y^2 + z^2 \geq 2(yz \cos \theta_1 + zx \cos \theta_2 + xy \cos \theta_3).$$

Proof. Using $\theta_3 = \pi - (\theta_1 + \theta_2)$, it's an easy job to check the following identity

$$x^2 + y^2 + z^2 - 2(yz \cos \theta_1 + zx \cos \theta_2 + xy \cos \theta_3) = (z - (x \cos \theta_2 + y \cos \theta_1))^2 + (x \sin \theta_2 - y \sin \theta_1)^2.$$

□

Corollary 1.3.1. *Let p, q , and r be positive real numbers. Let θ_1, θ_2 , and θ_3 be real numbers satisfying $\theta_1 + \theta_2 + \theta_3 = \pi$. Then, the following inequality holds.*

$$p \cos \theta_1 + q \cos \theta_2 + r \cos \theta_3 \leq \frac{1}{2} \left(\frac{qr}{p} + \frac{rp}{q} + \frac{pq}{r} \right).$$

Proof. Take $(x, y, z) = \left(\sqrt{\frac{qr}{p}}, \sqrt{\frac{rp}{q}}, \sqrt{\frac{pq}{r}} \right)$ and apply the above proposition. □

Theorem 1.3.2. (Barrow's Inequality) *Let P be an interior point of a triangle ABC and let U, V, W be the points where the bisectors of angles BPC, CPA, APB cut the sides BC, CA, AB respectively. Prove that $PA + PB + PC \geq 2(PU + PV + PW)$.*

Proof. ([MB] and [AK]) Let $d_1 = PA$, $d_2 = PB$, $d_3 = PC$, $l_1 = PU$, $l_2 = PV$, $l_3 = PW$, $2\theta_1 = \angle BPC$, $2\theta_2 = \angle CPA$, and $2\theta_3 = \angle APB$. We need to show that $d_1 + d_2 + d_3 \geq 2(l_1 + l_2 + l_3)$. It's easy to deduce the following identities

$$l_1 = \frac{2d_2d_3}{d_2 + d_3} \cos \theta_1, \quad l_2 = \frac{2d_3d_1}{d_3 + d_1} \cos \theta_2, \quad \text{and} \quad l_3 = \frac{2d_1d_2}{d_1 + d_2} \cos \theta_3,$$

By the AM-GM inequality and the above corollary, this means that

$$l_1 + l_2 + l_3 \leq \sqrt{d_2d_3} \cos \theta_1 + \sqrt{d_3d_1} \cos \theta_2 + \sqrt{d_1d_2} \cos \theta_3 \leq \frac{1}{2} (d_1 + d_2 + d_3).$$

□

As another application of the above trigonometric proposition, we establish the following inequality

Corollary 1.3.2. ([AK], Abi-Khuzam) *Let x_1, \dots, x_4 be positive real numbers. Let $\theta_1, \dots, \theta_4$ be real numbers such that $\theta_1 + \dots + \theta_4 = \pi$. Then,*

$$x_1 \cos \theta_1 + x_2 \cos \theta_2 + x_3 \cos \theta_3 + x_4 \cos \theta_4 \leq \sqrt{\frac{(x_1x_2 + x_3x_4)(x_1x_3 + x_2x_4)(x_1x_4 + x_2x_3)}{x_1x_2x_3x_4}}}.$$

Proof. Let $p = \frac{x_1^2 + x_2^2}{2x_1x_2} + \frac{x_3^2 + x_4^2}{2x_3x_4}$, $q = \frac{x_1x_2 + x_3x_4}{2}$ and $\lambda = \sqrt{\frac{p}{q}}$. In the view of $\theta_1 + \theta_2 + (\theta_3 + \theta_4) = \pi$ and $\theta_3 + \theta_4 + (\theta_1 + \theta_2) = \pi$, the proposition implies that

$$x_1 \cos \theta_1 + x_2 \cos \theta_2 + \lambda \cos(\theta_3 + \theta_4) \leq p\lambda = \sqrt{pq},$$

and

$$x_3 \cos \theta_3 + x_4 \cos \theta_4 + \lambda \cos(\theta_1 + \theta_2) \leq \frac{q}{\lambda} = \sqrt{pq}.$$

Since $\cos(\theta_3 + \theta_4) + \cos(\theta_1 + \theta_2) = 0$, adding these two above inequalities yields

$$x_1 \cos \theta_1 + x_2 \cos \theta_2 + x_3 \cos \theta_3 + x_4 \cos \theta_4 \leq 2\sqrt{pq} = \sqrt{\frac{(x_1x_2 + x_3x_4)(x_1x_3 + x_2x_4)(x_1x_4 + x_2x_3)}{x_1x_2x_3x_4}}}.$$

□

1.4 Applications of Complex Numbers

In this section, we discuss some applications of complex numbers to geometric inequality. Every complex number corresponds to a unique point in the complex plane. The standard symbol for the set of all complex numbers is \mathbb{C} , and we also refer to the complex plane as \mathbb{C} . The main tool is applications of the following fundamental inequality.

Theorem 1.4.1. *If $z_1, \dots, z_n \in \mathbb{C}$, then $|z_1| + \dots + |z_n| \geq |z_1 + \dots + z_n|$.*

Proof. Use induction on n with the triangle inequality. \square

Theorem 1.4.2. (Ptolemy's Inequality) *For any points A, B, C, D in the plane, we have*

$$\overline{AB} \cdot \overline{CD} + \overline{BC} \cdot \overline{DA} \geq \overline{AC} \cdot \overline{BD}.$$

Proof. Suppose that a, b, c and 0 are complex numbers that correspond to A, B, C, D . It becomes

$$|a - b| \cdot |c| + |b - c| \cdot |a| \geq |a - c| \cdot |b|.$$

Applying the Triangle Inequality to the identity $(a - b)c + (b - c)a = (a - c)b$, we get the result. \square

Problem 4. ([TD]) *Let P be an arbitrary point in the plane of a triangle ABC with the centroid G . Show the following inequalities*

- (1) $\overline{BC} \cdot \overline{PB} \cdot \overline{PC} + \overline{AB} \cdot \overline{PA} \cdot \overline{PB} + \overline{CA} \cdot \overline{PC} \cdot \overline{PA} \geq \overline{BC} \cdot \overline{CA} \cdot \overline{AB}$ and
- (2) $\overline{PA}^3 \cdot \overline{BC} + \overline{PB}^3 \cdot \overline{CA} + \overline{PC}^3 \cdot \overline{AB} \geq 3\overline{PG} \cdot \overline{BC} \cdot \overline{CA} \cdot \overline{AB}$.

Solution. We only prove the first inequality. Regard A, B, C, P as complex numbers and assume that P corresponds to 0 . We're required to prove that

$$|(B - C)BC| + |(A - B)AB| + |(C - A)CA| \geq |(B - C)(C - A)(A - B)|.$$

It remains to apply the Triangle Inequality to the identity

$$(B - C)BC + (A - B)AB + (C - A)CA = -(B - C)(C - A)(A - B).$$

\square

Problem 5. (IMO Short-list 2002) *Let ABC be a triangle for which there exists an interior point F such that $\angle AFB = \angle BFC = \angle CFA$. Let the lines BF and CF meet the sides AC and AB at D and E , respectively. Prove that $\overline{AB} + \overline{AC} \geq 4\overline{DE}$.*

Solution. Let $\overline{AF} = x, \overline{BF} = y, \overline{CF} = z$ and let $\omega = \cos \frac{2\pi}{3} + i \sin \frac{2\pi}{3}$. We can toss the pictures on \mathbb{C} so that the points F, A, B, C, D , and E are represented by the complex numbers $0, x, y\omega, z\omega^2, d$, and e . It's an easy exercise to establish that $\overline{DF} = \frac{xz}{x+z}$ and $\overline{EF} = \frac{xy}{x+y}$. This means that $d = -\frac{xz}{x+z}\omega$ and $e = -\frac{xy}{x+y}\omega$. We're now required to prove that

$$|x - y\omega| + |z\omega^2 - x| \geq 4 \left| \frac{-zx}{z+x}\omega + \frac{xy}{x+y}\omega^2 \right|.$$

Since $|\omega| = 1$ and $\omega^3 = 1$, we have $|z\omega^2 - x| = |\omega(z\omega^2 - x)| = |z - x\omega|$. Therefore, we need to prove

$$|x - y\omega| + |z - x\omega| \geq \left| \frac{4zx}{z+x} - \frac{4xy}{x+y}\omega \right|.$$

More strongly, we establish that $|(x - y\omega) + (z - x\omega)| \geq \left| \frac{4zx}{z+x} - \frac{4xy}{x+y}\omega \right|$ or $|p - q\omega| \geq |r - s\omega|$, where $p = z + x$, $q = y + x$, $r = \frac{4zx}{z+x}$ and $s = \frac{4xy}{x+y}$. It's clear that $p \geq r > 0$ and $q \geq s > 0$. It follows that

$$|p - q\omega|^2 - |r - s\omega|^2 = (p - q\omega)\overline{(p - q\omega)} - (r - s\omega)\overline{(r - s\omega)} = (p^2 - r^2) + (pq - rs) + (q^2 - s^2) \geq 0.$$

It's easy to check that the equality holds if and only if $\triangle ABC$ is equilateral. \square

Chapter 2

Four Basic Techniques

Differentiate! Shiing-shen Chern

2.1 Trigonometric Substitutions

If you are faced with an integral that contains square root expressions such as

$$\int \sqrt{1-x^2} dx, \quad \int \sqrt{1+y^2} dy, \quad \int \sqrt{z^2-1} dz$$

then trigonometric substitutions such as $x = \sin t$, $y = \tan t$, $z = \sec t$ are very useful. We will learn that making a suitable *trigonometric* substitution simplifies the given inequality.

Problem 6. (APMO 2004/5) *Prove that, for all positive real numbers a, b, c ,*

$$(a^2 + 2)(b^2 + 2)(c^2 + 2) \geq 9(ab + bc + ca).$$

First Solution. Choose $A, B, C \in (0, \frac{\pi}{2})$ with $a = \sqrt{2} \tan A$, $b = \sqrt{2} \tan B$, and $c = \sqrt{2} \tan C$. Using the well-known trigonometric identity $1 + \tan^2 \theta = \frac{1}{\cos^2 \theta}$, one may rewrite it as

$$\frac{4}{9} \geq \cos A \cos B \cos C (\cos A \sin B \sin C + \sin A \cos B \sin C + \sin A \sin B \cos C).$$

One may easily check the following trigonometric identity

$$\cos(A + B + C) = \cos A \cos B \cos C - \cos A \sin B \sin C - \sin A \cos B \sin C - \sin A \sin B \cos C.$$

Then, the above trigonometric inequality takes the form

$$\frac{4}{9} \geq \cos A \cos B \cos C (\cos A \cos B \cos C - \cos(A + B + C)).$$

Let $\theta = \frac{A+B+C}{3}$. Applying the AM-GM inequality and Jesen's inequality, we have

$$\cos A \cos B \cos C \leq \left(\frac{\cos A + \cos B + \cos C}{3} \right)^3 \leq \cos^3 \theta.$$

We now need to show that

$$\frac{4}{9} \geq \cos^3 \theta (\cos^3 \theta - \cos 3\theta).$$

Using the trigonometric identity

$$\cos 3\theta = 4 \cos^3 \theta - 3 \cos \theta \quad \text{or} \quad \cos 3\theta - \cos 3\theta = 3 \cos \theta - 3 \cos^3 \theta,$$

it becomes

$$\frac{4}{27} \geq \cos^4 \theta (1 - \cos^2 \theta),$$

which follows from the AM-GM inequality

$$\left(\frac{\cos^2 \theta}{2} \cdot \frac{\cos^2 \theta}{2} \cdot (1 - \cos^2 \theta) \right)^{\frac{1}{3}} \leq \frac{1}{3} \left(\frac{\cos^2 \theta}{2} + \frac{\cos^2 \theta}{2} + (1 - \cos^2 \theta) \right) = \frac{1}{3}.$$

One find that the equality holds if and only if $\tan A = \tan B = \tan C = \frac{1}{\sqrt{2}}$ if and only if $a = b = c = 1$. \square

Problem 7. (Latvia 2002) Let a, b, c, d be the positive real numbers such that

$$\frac{1}{1+a^4} + \frac{1}{1+b^4} + \frac{1}{1+c^4} + \frac{1}{1+d^4} = 1.$$

Prove that $abcd \geq 3$.

Solution. We can write $a^2 = \tan A, b^2 = \tan B, c^2 = \tan C, d^2 = \tan D$, where $A, B, C, D \in (0, \frac{\pi}{2})$. Then, the algebraic identity becomes the following trigonometric identity :

$$\cos^2 A + \cos^2 B + \cos^2 C + \cos^2 D = 1.$$

Applying the AM-GM inequality, we obtain

$$\sin^2 A = 1 - \cos^2 A = \cos^2 B + \cos^2 C + \cos^2 D \geq 3(\cos B \cos C \cos D)^{\frac{2}{3}}.$$

Similarly, we obtain

$$\sin^2 B \geq 3(\cos C \cos D \cos A)^{\frac{2}{3}}, \sin^2 C \geq 3(\cos D \cos A \cos B)^{\frac{2}{3}}, \text{ and } \sin^2 D \geq 3(\cos A \cos B \cos C)^{\frac{2}{3}}.$$

Multiplying these four inequalities, we get the result! \square

Problem 8. (Korea 1998) Let x, y, z be the positive reals with $x + y + z = xyz$. Show that

$$\frac{1}{\sqrt{1+x^2}} + \frac{1}{\sqrt{1+y^2}} + \frac{1}{\sqrt{1+z^2}} \leq \frac{3}{2}.$$

Since the function f is not concave on \mathbb{R}^+ , we cannot apply Jensen's inequality to the function $f(t) = \frac{1}{\sqrt{1+t^2}}$. However, the function $f(\tan \theta)$ is concave on $(0, \frac{\pi}{2})$!

First Solution. We can write $x = \tan A, y = \tan B, z = \tan C$, where $A, B, C \in (0, \frac{\pi}{2})$. Using the fact that $1 + \tan^2 \theta = \left(\frac{1}{\cos \theta}\right)^2$, we rewrite it in the terms of A, B, C :

$$\cos A + \cos B + \cos C \leq \frac{3}{2}.$$

It follows from $\tan(\pi - C) = -z = \frac{x+y}{1-xy} = \tan(A+B)$ and from $\pi - C, A+B \in (0, \pi)$ that $\pi - C = A+B$ or $A+B+C = \pi$. Hence, it suffices to show the following. \square

Theorem 2.1.1. In any acute triangle ABC , we have $\cos A + \cos B + \cos C \leq \frac{3}{2}$.

Proof. Since $\cos x$ is concave on $(0, \frac{\pi}{2})$, it's a direct consequence of Jensen's inequality. \square

We note that the function $\cos x$ is not concave on $(0, \pi)$. In fact, it's convex on $(\frac{\pi}{2}, \pi)$. One may think that the inequality $\cos A + \cos B + \cos C \leq \frac{3}{2}$ doesn't hold for any triangles. However, it's known that it holds for all triangles.

Theorem 2.1.2. In any triangle ABC , we have $\cos A + \cos B + \cos C \leq \frac{3}{2}$.

First Proof. It follows from $\pi - C = A+B$ that $\cos C = -\cos(A+B) = -\cos A \cos B + \sin A \sin B$ or

$$3 - 2(\cos A + \cos B + \cos C) = (\sin A - \sin B)^2 + (\cos A + \cos B - 1)^2 \geq 0.$$

\square

Second Proof. Let $BC = a$, $CA = b$, $AB = c$. Use the Cosine Law to rewrite the given inequality in the terms of a , b , c :

$$\frac{b^2 + c^2 - a^2}{2bc} + \frac{c^2 + a^2 - b^2}{2ca} + \frac{a^2 + b^2 - c^2}{2ab} \leq \frac{3}{2}.$$

Clearing denominators, this becomes

$$3abc \geq a(b^2 + c^2 - a^2) + b(c^2 + a^2 - b^2) + c(a^2 + b^2 - c^2),$$

which is equivalent to $abc \geq (b+c-a)(c+a-b)(a+b-c)$ in the theorem 2. \square

In the first chapter, we found that the *geometric* inequality $R \geq 2r$ is equivalent to the *algebraic* inequality $abc \geq (b+c-a)(c+a-b)(a+b-c)$. We now find that, in the proof of the above theorem, $abc \geq (b+c-a)(c+a-b)(a+b-c)$ is equivalent to the *trigonometric* inequality $\cos A + \cos B + \cos C \leq \frac{3}{2}$. One may ask that

In any triangles ABC , is there a *natural* relation between $\cos A + \cos B + \cos C$ and $\frac{R}{r}$, where R and r are the radii of the circumcircle and incircle of ABC ?

Theorem 2.1.3. *Let R and r denote the radii of the circumcircle and incircle of the triangle ABC . Then, we have $\cos A + \cos B + \cos C = 1 + \frac{r}{R}$.*

Proof. Use the identity $a(b^2 + c^2 - a^2) + b(c^2 + a^2 - b^2) + c(a^2 + b^2 - c^2) = 2abc + (b+c-a)(c+a-b)(a+b-c)$. We leave the details for the readers. \square

Exercise 4. (a) Let p, q, r be the positive real numbers such that $p^2 + q^2 + r^2 + 2pqr = 1$. Show that there exists an acute triangle ABC such that $p = \cos A$, $q = \cos B$, $r = \cos C$.

(b) Let $p, q, r \geq 0$ with $p^2 + q^2 + r^2 + 2pqr = 1$. Show that there are $A, B, C \in [0, \frac{\pi}{2}]$ with $p = \cos A$, $q = \cos B$, $r = \cos C$, and $A + B + C = \pi$.

Problem 9. (USA 2001) Let a, b , and c be nonnegative real numbers such that $a^2 + b^2 + c^2 + abc = 4$. Prove that $0 \leq ab + bc + ca - abc \leq 2$.

Solution. Notice that $a, b, c > 1$ implies that $a^2 + b^2 + c^2 + abc > 4$. If $a \leq 1$, then we have $ab + bc + ca - abc \geq (1-a)bc \geq 0$. We now prove that $ab + bc + ca - abc \leq 2$. Letting $a = 2p$, $b = 2q$, $c = 2r$, we get $p^2 + q^2 + r^2 + 2pqr = 1$. By the above exercise, we can write

$$a = 2\cos A, b = 2\cos B, c = 2\cos C \text{ for some } A, B, C \in \left[0, \frac{\pi}{2}\right] \text{ with } A + B + C = \pi.$$

We are required to prove

$$\cos A \cos B + \cos B \cos C + \cos C \cos A - 2\cos A \cos B \cos C \leq \frac{1}{2}.$$

One may assume that $A \geq \frac{\pi}{3}$ or $1 - 2\cos A \geq 0$. Note that

$$\cos A \cos B + \cos B \cos C + \cos C \cos A - 2\cos A \cos B \cos C = \cos A(\cos B + \cos C) + \cos B \cos C(1 - 2\cos A).$$

We apply Jensen's inequality to deduce $\cos B + \cos C \leq \frac{3}{2} - \cos A$. Note that $2\cos B \cos C = \cos(B - C) + \cos(B + C) \leq 1 - \cos A$. These imply that

$$\cos A(\cos B + \cos C) + \cos B \cos C(1 - 2\cos A) \leq \cos A \left(\frac{3}{2} - \cos A \right) + \left(\frac{1 - \cos A}{2} \right) (1 - 2\cos A).$$

However, it's easy to verify that $\cos A \left(\frac{3}{2} - \cos A \right) + \left(\frac{1 - \cos A}{2} \right) (1 - 2\cos A) = \frac{1}{2}$. \square

2.2 Algebraic Substitutions

We know that some inequalities in triangle geometry can be treated by the *Ravi* substitution and *trigonometric* substitutions. We can also transform the given inequalities into easier ones through some clever *algebraic* substitutions.

Problem 10. (IMO 2001/2) Let a, b, c be positive real numbers. Prove that

$$\frac{a}{\sqrt{a^2 + 8bc}} + \frac{b}{\sqrt{b^2 + 8ca}} + \frac{c}{\sqrt{c^2 + 8ab}} \geq 1.$$

First Solution. To remove the square roots, we make the following substitution :

$$x = \frac{a}{\sqrt{a^2 + 8bc}}, \quad y = \frac{b}{\sqrt{b^2 + 8ca}}, \quad z = \frac{c}{\sqrt{c^2 + 8ab}}.$$

Clearly, $x, y, z \in (0, 1)$. Our aim is to show that $x + y + z \geq 1$. We notice that

$$\frac{a^2}{8bc} = \frac{x^2}{1-x^2}, \quad \frac{b^2}{8ac} = \frac{y^2}{1-y^2}, \quad \frac{c^2}{8ab} = \frac{z^2}{1-z^2} \implies \frac{1}{512} = \left(\frac{x^2}{1-x^2} \right) \left(\frac{y^2}{1-y^2} \right) \left(\frac{z^2}{1-z^2} \right).$$

Hence, we need to show that

$$x + y + z \geq 1, \text{ where } 0 < x, y, z < 1 \text{ and } (1-x^2)(1-y^2)(1-z^2) = 512(xyz)^2.$$

However, $1 > x + y + z$ implies that, by the AM-GM inequality,

$$\begin{aligned} (1-x^2)(1-y^2)(1-z^2) &> ((x+y+z)^2 - x^2)((x+y+z)^2 - y^2)((x+y+z)^2 - z^2) = (x+x+y+z)(y+z) \\ (x+y+z)(z+x)(x+y+z+z)(x+y) &\geq 4(x^2yz)^{\frac{1}{4}} \cdot 2(yz)^{\frac{1}{2}} \cdot 4(y^2zx)^{\frac{1}{4}} \cdot 2(zx)^{\frac{1}{2}} \cdot 4(z^2xy)^{\frac{1}{4}} \cdot 2(xy)^{\frac{1}{2}} \\ &= 512(xyz)^2. \text{ This is a contradiction!} \end{aligned}$$

Problem 11. (IMO 1995/2) Let a, b, c be positive numbers such that $abc = 1$. Prove that

$$\frac{1}{a^3(b+c)} + \frac{1}{b^3(c+a)} + \frac{1}{c^3(a+b)} \geq \frac{3}{2}.$$

First Solution. After the substitution $a = \frac{1}{x}$, $b = \frac{1}{y}$, $c = \frac{1}{z}$, we get $xyz = 1$. The inequality takes the form

$$\frac{x^2}{y+z} + \frac{y^2}{z+x} + \frac{z^2}{x+y} \geq \frac{3}{2}.$$

It follows from the Cauchy-Schwarz inequality that

$$[(y+z) + (z+x) + (x+y)] \left(\frac{x^2}{y+z} + \frac{y^2}{z+x} + \frac{z^2}{x+y} \right) \geq (x+y+z)^2$$

so that, by the AM-GM inequality,

$$\frac{x^2}{y+z} + \frac{y^2}{z+x} + \frac{z^2}{x+y} \geq \frac{x+y+z}{2} \geq \frac{3(xyz)^{\frac{1}{3}}}{2} = \frac{3}{2}.$$

□

(Korea 1998) Let x, y, z be the positive reals with $x + y + z = xyz$. Show that

$$\frac{1}{\sqrt{1+x^2}} + \frac{1}{\sqrt{1+y^2}} + \frac{1}{\sqrt{1+z^2}} \leq \frac{3}{2}.$$

Second Solution. The starting point is letting $a = \frac{1}{x}$, $b = \frac{1}{y}$, $c = \frac{1}{z}$. We find that $a+b+c = abc$ is equivalent to $1 = xy + yz + zx$. The inequality becomes

$$\frac{x}{\sqrt{x^2+1}} + \frac{y}{\sqrt{y^2+1}} + \frac{z}{\sqrt{z^2+1}} \leq \frac{3}{2}$$

or

$$\frac{x}{\sqrt{x^2+xy+yz+zx}} + \frac{y}{\sqrt{y^2+xy+yz+zx}} + \frac{z}{\sqrt{z^2+xy+yz+zx}} \leq \frac{3}{2}$$

or

$$\frac{x}{\sqrt{(x+y)(x+z)}} + \frac{y}{\sqrt{(y+z)(y+x)}} + \frac{z}{\sqrt{(z+x)(z+y)}} \leq \frac{3}{2}.$$

By the AM-GM inequality, we have

$$\frac{x}{\sqrt{(x+y)(x+z)}} = \frac{x\sqrt{(x+y)(x+z)}}{(x+y)(x+z)} \leq \frac{1}{2} \frac{x[(x+y)+(x+z)]}{(x+y)(x+z)} = \frac{1}{2} \left(\frac{x}{x+z} + \frac{x}{x+y} \right).$$

In a like manner, we obtain

$$\frac{y}{\sqrt{(y+z)(y+x)}} \leq \frac{1}{2} \left(\frac{y}{y+z} + \frac{y}{y+x} \right) \quad \text{and} \quad \frac{z}{\sqrt{(z+x)(z+y)}} \leq \frac{1}{2} \left(\frac{z}{z+x} + \frac{z}{z+y} \right).$$

Adding these three yields the required result. \square

We now prove a classical theorem in various ways.

Theorem 2.2.1. (Nesbitt, 1903) *For all positive real numbers a, b, c , we have*

$$\frac{a}{b+c} + \frac{b}{c+a} + \frac{c}{a+b} \geq \frac{3}{2}.$$

Proof 1. After the substitution $x = b+c$, $y = c+a$, $z = a+b$, it becomes

$$\sum_{\text{cyclic}} \frac{y+z-x}{2x} \geq \frac{3}{2} \quad \text{or} \quad \sum_{\text{cyclic}} \frac{y+z}{x} \geq 6,$$

which follows from the AM-GM inequality as following:

$$\sum_{\text{cyclic}} \frac{y+z}{x} = \frac{y}{x} + \frac{z}{x} + \frac{z}{y} + \frac{x}{y} + \frac{x}{z} + \frac{y}{z} \geq 6 \left(\frac{y}{x} \cdot \frac{z}{x} \cdot \frac{z}{y} \cdot \frac{x}{y} \cdot \frac{x}{z} \cdot \frac{y}{z} \right)^{\frac{1}{6}} = 6.$$

Proof 2. We make the substitution

$$x = \frac{a}{b+c}, \quad y = \frac{b}{c+a}, \quad z = \frac{c}{a+b}.$$

It follows that

$$\sum_{\text{cyclic}} f(x) = \sum_{\text{cyclic}} \frac{a}{a+b+c} = 1, \quad \text{where } f(t) = \frac{t}{1+t}.$$

Since f is concave on $(0, \infty)$, Jensen's inequality shows that

$$f\left(\frac{1}{2}\right) = \frac{1}{3} = \frac{1}{3} \sum_{\text{cyclic}} f(x) \leq f\left(\frac{x+y+z}{3}\right) \quad \text{or} \quad f\left(\frac{1}{2}\right) \leq f\left(\frac{x+y+z}{3}\right).$$

Since f is monotone increasing, this implies that

$$\frac{1}{2} \leq \frac{x+y+z}{3} \quad \text{or} \quad \sum_{\text{cyclic}} \frac{a}{b+c} = x+y+z \geq \frac{3}{2}.$$

Proof 3. As in the previous proof, it suffices to show that

$$T \geq \frac{1}{2}, \text{ where } T = \frac{x+y+z}{3} \text{ and } \sum_{\text{cyclic}} \frac{x}{1+x} = 1.$$

One can easily check that the condition

$$\sum_{\text{cyclic}} \frac{x}{1+x} = 1$$

becomes $1 = 2xyz + xy + yz + zx$. By the AM-GM inequality, we have

$$1 = 2xyz + xy + yz + zx \leq 2T^3 + 3T^2 \Rightarrow 2T^3 + 3T^2 - 1 \geq 0 \Rightarrow (2T-1)(T+1)^2 \geq 0 \Rightarrow T \geq \frac{1}{2}.$$

(IMO 2000/2) Let a, b, c be positive numbers such that $abc = 1$. Prove that

$$\left(a - 1 + \frac{1}{b}\right) \left(b - 1 + \frac{1}{c}\right) \left(c - 1 + \frac{1}{a}\right) \leq 1.$$

Second Solution. ([IV], Ilan Vardi) Since $abc = 1$, we may assume that $a \geq 1 \geq b$. ¹ It follows that

$$1 - \left(a - 1 + \frac{1}{b}\right) \left(b - 1 + \frac{1}{c}\right) \left(c - 1 + \frac{1}{a}\right) = \left(c + \frac{1}{c} - 2\right) \left(a + \frac{1}{b} - 1\right) + \frac{(a-1)(1-b)}{a}. \quad ^2$$

□

Third Solution. As in the first solution, after the substitution $a = \frac{x}{y}$, $b = \frac{y}{z}$, $c = \frac{z}{x}$ for $x, y, z > 0$, we can rewrite it as $xyz \geq (y+z-x)(z+x-y)(x+y-z)$. Without loss of generality, we can assume that $z \geq y \geq x$. Set $y-x = p$ and $z-x = q$ with $p, q \geq 0$. It's straightforward to verify that

$$xyz - (y+z-x)(z+x-y)(x+y-z) = (p^2 - pq + q^2)x + (p^3 + q^3 - p^2q - pq^2).$$

Since $p^2 - pq + q^2 \geq (p-q)^2 \geq 0$ and $p^3 + q^3 - p^2q - pq^2 = (p-q)^2(p+q) \geq 0$, we get the result. □

Fourth Solution. (From the IMO 2000 Short List) Using the condition $abc = 1$, it's straightforward to verify the equalities

$$\begin{aligned} 2 &= \frac{1}{a} \left(a - 1 + \frac{1}{b}\right) + c \left(b - 1 + \frac{1}{c}\right), \\ 2 &= \frac{1}{b} \left(b - 1 + \frac{1}{c}\right) + a \left(c - 1 + \frac{1}{a}\right), \\ 2 &= \frac{1}{c} \left(c - 1 + \frac{1}{a}\right) + b \left(a - 1 + \frac{1}{b}\right). \end{aligned}$$

In particular, they show that at most one of the numbers $u = a - 1 + \frac{1}{b}$, $v = b - 1 + \frac{1}{c}$, $w = c - 1 + \frac{1}{a}$ is negative. If there is such a number, we have

$$\left(a - 1 + \frac{1}{b}\right) \left(b - 1 + \frac{1}{c}\right) \left(c - 1 + \frac{1}{a}\right) = uvw < 0 < 1.$$

And if $u, v, w \geq 0$, the AM-GM inequality yields

$$2 = \frac{1}{a}u + cv \geq 2\sqrt{\frac{c}{a}uv}, \quad 2 = \frac{1}{b}v + aw \geq 2\sqrt{\frac{a}{b}vw}, \quad 2 = \frac{1}{c}w + au \geq 2\sqrt{\frac{b}{c}wu}.$$

Thus, $uv \leq \frac{a}{c}$, $vw \leq \frac{b}{a}$, $wu \leq \frac{c}{b}$, so $(uvw)^2 \leq \frac{a}{c} \cdot \frac{b}{a} \cdot \frac{c}{b} = 1$. Since $u, v, w \geq 0$, this completes the proof. □

¹Why? Note that the inequality is not symmetric in the three variables. Check it!

²For a verification of the identity, see [IV].

Problem 12. Let a, b, c be positive real numbers satisfying $a + b + c = 1$. Show that

$$\frac{a}{a+bc} + \frac{b}{b+ca} + \frac{\sqrt{abc}}{c+ab} \leq 1 + \frac{3\sqrt{3}}{4}.$$

Solution. We want to establish that

$$\frac{1}{1+\frac{bc}{a}} + \frac{1}{1+\frac{ca}{b}} + \frac{\sqrt{\frac{ab}{c}}}{1+\frac{ab}{c}} \leq 1 + \frac{3\sqrt{3}}{4}.$$

Set $x = \sqrt{\frac{bc}{a}}$, $y = \sqrt{\frac{ca}{b}}$, $z = \sqrt{\frac{ab}{c}}$. We need to prove that

$$\frac{1}{1+x^2} + \frac{1}{1+y^2} + \frac{z}{1+z^2} \leq 1 + \frac{3\sqrt{3}}{4},$$

where $x, y, z > 0$ and $xy + yz + zx = 1$. It's not hard to show that there exists $A, B, C \in (0, \pi)$ with

$$x = \tan \frac{A}{2}, y = \tan \frac{B}{2}, z = \tan \frac{C}{2}, \text{ and } A + B + C = \pi.$$

The inequality becomes

$$\frac{1}{1 + (\tan \frac{A}{2})^2} + \frac{1}{1 + (\tan \frac{B}{2})^2} + \frac{\tan \frac{C}{2}}{1 + (\tan \frac{C}{2})^2} \leq 1 + \frac{3\sqrt{3}}{4}$$

or

$$1 + \frac{1}{2} (\cos A + \cos B + \sin C) \leq 1 + \frac{3\sqrt{3}}{4}$$

or

$$\cos A + \cos B + \sin C \leq \frac{3\sqrt{3}}{2}.$$

□

Note that $\cos A + \cos B = 2 \cos \left(\frac{A+B}{2} \right) \cos \left(\frac{A-B}{2} \right)$. Since $\left| \frac{A-B}{2} \right| < \frac{\pi}{2}$, this means that

$$\cos A + \cos B \leq 2 \cos \left(\frac{A+B}{2} \right) = 2 \cos \left(\frac{\pi - C}{2} \right).$$

It will be enough to show that

$$2 \cos \left(\frac{\pi - C}{2} \right) + \sin C \leq \frac{3\sqrt{3}}{2},$$

where $C \in (0, \pi)$. This is a one-variable inequality.³ It's left as an exercise for the reader.

Problem 13. (Iran 1998) Prove that, for all $x, y, z > 1$ such that $\frac{1}{x} + \frac{1}{y} + \frac{1}{z} = 2$,

$$\sqrt{x+y+z} \geq \sqrt{x-1} + \sqrt{y-1} + \sqrt{z-1}.$$

First Solution. We begin with the algebraic substitution $a = \sqrt{x-1}$, $b = \sqrt{y-1}$, $c = \sqrt{z-1}$. Then, the condition becomes

$$\frac{1}{1+a^2} + \frac{1}{1+b^2} + \frac{1}{1+c^2} = 2 \Leftrightarrow a^2b^2 + b^2c^2 + c^2a^2 + 2a^2b^2c^2 = 1$$

and the inequality is equivalent to

$$\sqrt{a^2 + b^2 + c^2 + 3} \geq a + b + c \Leftrightarrow ab + bc + ca \leq \frac{3}{2}.$$

Let $p = bc$, $q = ca$, $r = ab$. Our job is to prove that $p + q + r \leq \frac{3}{2}$ where $p^2 + q^2 + r^2 + 2pqr = 1$. By the exercise 7, we can make the trigonometric substitution

$$p = \cos A, q = \cos B, r = \cos C \text{ for some } A, B, C \in \left(0, \frac{\pi}{2}\right) \text{ with } A + B + C = \pi.$$

What we need to show is now that $\cos A + \cos B + \cos C \leq \frac{3}{2}$. It follows from Jensen's inequality. □

³ Differentiate! Shiing-shen Chern

2.3 Increasing Function Theorem

Theorem 2.3.1. (Increasing Function Theorem) Let $f : (a, b) \rightarrow \mathbb{R}$ be a differentiable function. If $f'(x) \geq 0$ for all $x \in (a, b)$, then f is monotone increasing on (a, b) . If $f'(x) > 0$ for all $x \in (a, b)$, then f is strictly increasing on (a, b) .

Proof. We first consider the case when $f'(x) > 0$ for all $x \in (a, b)$. Let $a < x_1 < x_2 < b$. We want to show that $f(x_1) < f(x_2)$. Applying the Mean Value Theorem, we find some $c \in (x_1, x_2)$ such that $f(x_2) - f(x_1) = f'(c)(x_2 - x_1)$. Since $f'(c) > 0$, this equation means that $f(x_2) - f(x_1) > 0$. In case when $f'(x) \geq 0$ for all $x \in (a, b)$, we can also apply the Mean Value Theorem to get the result. \square

Problem 14. (Ireland 2000) Let $x, y \geq 0$ with $x + y = 2$. Prove that $x^2y^2(x^2 + y^2) \leq 2$.

First Solution. After homogenizing, we need to prove

$$2 \left(\frac{x+y}{2} \right)^6 \geq x^2y^2(x^2 + y^2) \text{ or } (x+y)^6 \geq 32x^2y^2(x^2 + y^2).$$

(Now, forget the constraint $x+y = 2$!) In case $xy = 0$, it clearly holds. We now assume that $xy \neq 0$. Because of the homogeneity of the inequality, this means that we may normalize to $xy = 1$. Then, it becomes

$$\left(x + \frac{1}{x} \right)^6 \geq 32 \left(x^2 + \frac{1}{x^2} \right) \text{ or } p^3 \geq 32(p-2).$$

where $p = \left(x + \frac{1}{x} \right)^2 \geq 4$. Our job is now to minimize $F(p) = p^3 - 32(p-2)$ on $[4, \infty)$. Since $F'(p) = 3p^2 - 32 \geq 0$, where $p \geq \sqrt{\frac{32}{3}}$, F is (monotone) increasing on $[4, \infty)$. So, $F(p) \geq F(4) = 0$ for all $p \geq 4$. \square

Second Solution. As in the first solution, we prove that $(x+y)^6 \geq 32(x^2 + y^2)(xy)^2$ for all $x, y \geq 0$. In case $x = y = 0$, it's clear. Now, if $x^2 + y^2 > 0$, then we may normalize to $x^2 + y^2 = 2$. Setting $p = xy$, we have $0 \leq p \leq \frac{x^2+y^2}{2} = 1$ and $(x+y)^2 = x^2 + y^2 + 2xy = 2 + 2p$. It now becomes

$$(2 + 2p)^3 \geq 64p^2 \text{ or } p^3 - 5p^2 + 3p + 1 \geq 0.$$

We want to minimize $F(p) = p^3 - 5p^2 + 3p + 1$ on $[0, 1]$. We compute $F'(p) = 3(p - \frac{1}{3})(p - 3)$. We find that F is monotone increasing on $[0, \frac{1}{3}]$ and monotone decreasing on $[\frac{1}{3}, 1]$. Since $F(0) = 1$ and $F(1) = 0$, we conclude that $F(p) \geq F(1) = 0$ for all $p \in [0, 1]$. \square

Third Solution. We show that $(x+y)^6 \geq 32(x^2 + y^2)(xy)^2$ for all $x, y \geq 0$. We make the substitution $u = x + y$ and $v = x - y$. Then, we have $u \geq v \geq 0$. It becomes

$$u^6 \geq 32 \left(\frac{u^2 + v^2}{2} \right) \left(\frac{u^2 - v^2}{4} \right)^2 \text{ or } u^6 \geq (u^2 + v^2)(u^2 - v^2)^2.$$

Note that $u^4 \geq u^4 - v^4 \geq 0$ and that $u^2 \geq u^2 - v^2 \geq 0$. So, $u^6 \geq (u^4 - v^4)(u^2 - v^2) = (u^2 + v^2)(u^2 - v^2)^2$. \square

Problem 15. (IMO 1984/1) Let x, y, z be nonnegative real numbers such that $x + y + z = 1$. Prove that $0 \leq xy + yz + zx - 2xyz \leq \frac{7}{27}$.

First Solution. Let $f(x, y, z) = xy + yz + zx - 2xyz$. We may assume that $0 \leq x \leq y \leq z \leq 1$. Since $x + y + z = 1$, we find that $x \leq \frac{1}{3}$. It follows that $f(x, y, z) = (1 - 3x)yz + xyz + zx + xy \geq 0$. Applying the AM-GM inequality, we obtain $yz \leq \left(\frac{y+z}{2} \right)^2 = \left(\frac{1-x}{2} \right)^2$. Since $1 - 2x \geq 0$, this implies that

$$f(x, y, z) = x(y+z) + yz(1-2x) \leq x(1-x) + \left(\frac{1-x}{2} \right)^2 (1-2x) = \frac{-2x^3 + x^2 + 1}{4}.$$

Our job is now to maximize $F(x) = \frac{1}{4}(-2x^3 + x^2 + 1)$, where $x \in [0, \frac{1}{3}]$. Since $F'(x) = \frac{3}{2}x(\frac{1}{3} - x) \geq 0$ on $[0, \frac{1}{3}]$, we conclude that $F(x) \leq F(\frac{1}{3}) = \frac{7}{27}$ for all $x \in [0, \frac{1}{3}]$. \square

(IMO 2000/2) Let a, b, c be positive numbers such that $abc = 1$. Prove that

$$\left(a - 1 + \frac{1}{b}\right) \left(b - 1 + \frac{1}{c}\right) \left(c - 1 + \frac{1}{a}\right) \leq 1.$$

Fifth Solution. (based on work by an IMO 2000 contestant from Japan) Since $abc = 1$, at least one of a, b, c is greater than or equal to 1. Say $b \geq 1$. Putting $c = \frac{1}{ab}$, it becomes

$$\left(a - 1 + \frac{1}{b}\right) (b - 1 + ab) \left(\frac{1}{ab} - 1 + \frac{1}{a}\right) \leq 1$$

or

$$a^3b^3 - a^2b^3 - ab^3 - a^2b^2 + 3ab^2 - ab + b^3 - b^2 - b + 1 \geq 0.$$

Setting $x = ab$, it becomes $f_b(x) \geq 0$, where

$$f_b(t) = t^3 + b^3 - b^2t - bt^2 + 3bt - t^2 - b^2 - t - b + 1.$$

Fix a positive number $b \geq 1$. We need to show that $F(t) := f_b(t) \geq 0$ for all $t \geq 0$. It follows from $b \geq 1$ that the cubic polynomial $F'(t) = 3t^2 - 2(b+1)t - (b^2 - 3b + 1)$ has two real roots

$$\frac{b+1 - \sqrt{4b^2 - 7b + 4}}{3} \quad \text{and} \quad \lambda = \frac{b+1 + \sqrt{4b^2 - 7b + 4}}{3}.$$

Since F has a local minimum at $t = \lambda$, we find that $F(t) \geq \min\{F(0), F(\lambda)\}$ for all $t \geq 0$. We have to prove that $F(0) \geq 0$ and $F(\lambda) \geq 0$. We have $F(0) = b^3 - b^2 - b + 1 = (b-1)^2(b+1) \geq 0$. It remains to show that $F(\lambda) \geq 0$. Notice that λ is a root of $F'(t)$. After long division, we get

$$F(t) = F'(t) \left(\frac{1}{3}t - \frac{b+1}{9}\right) + \frac{1}{9}((-8b^2 + 14b - 8)t + 8b^3 - 7b^2 - 7b + 8).$$

Putting $t = \lambda$, we have

$$F(\lambda) = \frac{1}{9}((-8b^2 + 14b - 8)\lambda + 8b^3 - 7b^2 - 7b + 8).$$

Thus, our job is now to establish that, for all $b \geq 0$,

$$(-8b^2 + 14b - 8) \left(\frac{b+1 + \sqrt{4b^2 - 7b + 4}}{3}\right) + 8b^3 - 7b^2 - 7b + 8 \geq 0,$$

which is equivalent to

$$16b^3 - 15b^2 - 15b + 16 \geq (8b^2 - 14b + 8)\sqrt{4b^2 - 7b + 4}.$$

Since both $16b^3 - 15b^2 - 15b + 16$ and $8b^2 - 14b + 8$ are positive,⁴ it's equivalent to

$$(16b^3 - 15b^2 - 15b + 16)^2 \geq (8b^2 - 14b + 8)^2(4b^2 - 7b + 4)$$

or

$$864b^5 - 3375b^4 + 5022b^3 - 3375b^2 + 864b \geq 0 \quad \text{or} \quad 864b^4 - 3375b^3 + 5022b^2 - 3375b + 864 \geq 0.$$

Let $G(x) = 864x^4 - 3375x^3 + 5022x^2 - 3375x + 864$. We prove that $G(x) \geq 0$ for all $x \in \mathbb{R}$. We find that

$$G'(x) = 3456x^3 - 10125x^2 + 10044x - 3375 = (x-1)(3456x^2 - 6669x + 3375).$$

Since $3456x^2 - 6669x + 3375 > 0$ for all $x \in \mathbb{R}$, we find that $G(x)$ and $x-1$ have the same sign. It follows that G is monotone decreasing on $(-\infty, 1]$ and monotone increasing on $[1, \infty)$. We conclude that G has the global minimum at $x = 1$. Hence, $G(x) \geq G(1) = 0$ for all $x \in \mathbb{R}$. \square

⁴It's easy to check that $16b^3 - 15b^2 - 15b + 16 = 16(b^3 - b^2 - b + 1) + b^2 + b > 16(b^2 - 1)(b - 1) \geq 0$ and $8b^2 - 14b + 8 = 8(b-1)^2 + 2b > 0$.

2.4 Establishing New Bounds

We first give two alternative ways to prove Nesbitt's inequality.

(Nesbitt) For all positive real numbers a, b, c , we have

$$\frac{a}{b+c} + \frac{b}{c+a} + \frac{c}{a+b} \geq \frac{3}{2}.$$

Proof 4. From $\left(\frac{a}{b+c} - \frac{1}{2}\right)^2 \geq 0$, we deduce that

$$\frac{a}{b+c} \geq \frac{1}{4} \cdot \frac{\frac{8a}{b+c} - 1}{\frac{a}{b+c} + 1} = \frac{8a - b - c}{4(a+b+c)}.$$

It follows that

$$\sum_{\text{cyclic}} \frac{a}{b+c} \geq \sum_{\text{cyclic}} \frac{8a - b - c}{4(a+b+c)} = \frac{3}{2}.$$

Proof 5. We claim that

$$\frac{a}{b+c} \geq \frac{3a^{\frac{3}{2}}}{2(a^{\frac{3}{2}} + b^{\frac{3}{2}} + c^{\frac{3}{2}})} \text{ or } 2\left(a^{\frac{3}{2}} + b^{\frac{3}{2}} + c^{\frac{3}{2}}\right) \geq 3a^{\frac{1}{2}}(b+c).$$

The AM-GM inequality gives $a^{\frac{3}{2}} + b^{\frac{3}{2}} + c^{\frac{3}{2}} \geq 3a^{\frac{1}{2}}b$ and $a^{\frac{3}{2}} + c^{\frac{3}{2}} + b^{\frac{3}{2}} \geq 3a^{\frac{1}{2}}c$. Adding these two inequalities yields $2\left(a^{\frac{3}{2}} + b^{\frac{3}{2}} + c^{\frac{3}{2}}\right) \geq 3a^{\frac{1}{2}}(b+c)$, as desired. Therefore, we have

$$\sum_{\text{cyclic}} \frac{a}{b+c} \geq \frac{3}{2} \sum_{\text{cyclic}} \frac{a^{\frac{3}{2}}}{a^{\frac{3}{2}} + b^{\frac{3}{2}} + c^{\frac{3}{2}}} = \frac{3}{2}.$$

Some cyclic inequalities can be proved by finding new bounds. Suppose that we want to establish that

$$\sum_{\text{cyclic}} F(x, y, z) \geq C.$$

If a function G satisfies

- (1) $F(x, y, z) \geq G(x, y, z)$ for all $x, y, z > 0$, and
- (2) $\sum_{\text{cyclic}} G(x, y, z) = C$ for all $x, y, z > 0$,

then, we deduce that

$$\sum_{\text{cyclic}} F(x, y, z) \geq \sum_{\text{cyclic}} G(x, y, z) = C.$$

For example, if a function F satisfies

$$F(x, y, z) \geq \frac{x}{x+y+z}$$

for all $x, y, z > 0$, then, taking the cyclic sum yields

$$\sum_{\text{cyclic}} F(x, y, z) \geq 1.$$

As we saw in the above two proofs of Nesbitt's inequality, there are various lower bounds.

Problem 16. Let a, b, c be the lengths of a triangle. Show that

$$\frac{a}{b+c} + \frac{b}{c+a} + \frac{c}{a+b} < 2.$$

Proof. We don't employ the Ravi substitution. It follows from the triangle inequality that

$$\sum_{\text{cyclic}} \frac{a}{b+c} < \sum_{\text{cyclic}} \frac{a}{\frac{1}{2}(a+b+c)} = 2.$$

□

One day, I tried finding a new lower bound of $(x+y+z)^2$ where $x, y, z > 0$. There are well-known lower bounds such as $3(xy+yz+zx)$ and $9(xyz)^{\frac{2}{3}}$. But I wanted to find quite different one. I tried breaking the symmetry of the three variables x, y, z . Note that

$$(x+y+z)^2 = x^2 + y^2 + z^2 + xy + yz + zx + zx + zx.$$

I applied the AM-GM inequality to the right hand side except the term x^2 :

$$y^2 + z^2 + xy + xy + yz + yz + zx + zx \geq 8x^{\frac{1}{2}}y^{\frac{3}{4}}z^{\frac{3}{4}}.$$

It follows that

$$(x+y+z)^2 \geq x^2 + 8x^{\frac{1}{2}}y^{\frac{3}{4}}z^{\frac{3}{4}} = x^{\frac{1}{2}} \left(x^{\frac{3}{2}} + 8y^{\frac{3}{4}}z^{\frac{3}{4}} \right).$$

(IMO 2001/2) Let a, b, c be positive real numbers. Prove that

$$\frac{a}{\sqrt{a^2 + 8bc}} + \frac{b}{\sqrt{b^2 + 8ca}} + \frac{c}{\sqrt{c^2 + 8ab}} \geq 1.$$

Second Solution. We find that the above inequality also gives another lower bound of $x+y+z$, that is,

$$x+y+z \geq \sqrt{x^{\frac{1}{2}} \left(x^{\frac{3}{2}} + 8y^{\frac{3}{4}}z^{\frac{3}{4}} \right)}.$$

It follows that

$$\sum_{\text{cyclic}} \frac{x^{\frac{3}{4}}}{\sqrt{x^{\frac{3}{2}} + 8y^{\frac{3}{4}}z^{\frac{3}{4}}}} \geq \sum_{\text{cyclic}} \frac{x}{x+y+z} = 1.$$

After the substitution $x = a^{\frac{4}{3}}, y = b^{\frac{4}{3}}$, and $z = c^{\frac{4}{3}}$, it now becomes

$$\sum_{\text{cyclic}} \frac{a}{\sqrt{a^2 + 8bc}} \geq 1.$$

□

Problem 17. (IMO 2005/3) Let x, y , and z be positive numbers such that $xyz \geq 1$. Prove that

$$\frac{x^5 - x^2}{x^5 + y^2 + z^2} + \frac{y^5 - y^2}{y^5 + z^2 + x^2} + \frac{z^5 - z^2}{z^5 + x^2 + y^2} \geq 0.$$

First Solution. It's equivalent to the following inequality

$$\left(\frac{x^2 - x^5}{x^5 + y^2 + z^2} + 1 \right) + \left(\frac{y^2 - y^5}{y^5 + z^2 + x^2} + 1 \right) + \left(\frac{z^2 - z^5}{z^5 + x^2 + y^2} + 1 \right) \leq 3$$

or

$$\frac{x^2 + y^2 + z^2}{x^5 + y^2 + z^2} + \frac{x^2 + y^2 + z^2}{y^5 + z^2 + x^2} + \frac{x^2 + y^2 + z^2}{z^5 + x^2 + y^2} \leq 3.$$

With the Cauchy-Schwarz inequality and the fact that $xyz \geq 1$, we have

$$(x^5 + y^2 + z^2)(yz + y^2 + z^2) \geq (x^2 + y^2 + z^2)^2 \text{ or } \frac{x^2 + y^2 + z^2}{x^5 + y^2 + z^2} \leq \frac{yz + y^2 + z^2}{x^2 + y^2 + z^2}.$$

Taking the cyclic sum and $x^2 + y^2 + z^2 \geq xy + yz + zx$ give us

$$\frac{x^2 + y^2 + z^2}{x^5 + y^2 + z^2} + \frac{x^2 + y^2 + z^2}{y^5 + z^2 + x^2} + \frac{x^2 + y^2 + z^2}{z^5 + x^2 + y^2} \leq 2 + \frac{xy + yz + zx}{x^2 + y^2 + z^2} \leq 3.$$

□

Second Solution. The main idea is to think of 1 as follows :

$$\frac{x^5}{x^5 + y^2 + z^2} + \frac{y^5}{y^5 + z^2 + x^2} + \frac{z^5}{z^5 + x^2 + y^2} \geq 1 \geq \frac{x^2}{x^5 + y^2 + z^2} + \frac{y^2}{y^5 + z^2 + x^2} + \frac{z^2}{z^5 + x^2 + y^2}.$$

We first show the left-hand. It follows from $y^4 + z^4 \geq y^3z + yz^3 = yz(y^2 + z^2)$ that

$$x(y^4 + z^4) \geq xyz(y^2 + z^2) \geq y^2 + z^2 \quad \text{or} \quad \frac{x^5}{x^5 + y^2 + z^2} \geq \frac{x^5}{x^5 + xy^4 + xz^4} = \frac{x^4}{x^4 + y^4 + z^4}.$$

Taking the cyclic sum, we have the required inequality. It remains to show the right-hand.

[First Way] As in the first solution, the Cauchy-Schwarz inequality and $xyz \geq 1$ imply that

$$(x^5 + y^2 + z^2)(yz + y^2 + z^2) \geq (x^2 + y^2 + z^2)^2 \quad \text{or} \quad \frac{x^2(yz + y^2 + z^2)}{(x^2 + y^2 + z^2)^2} \geq \frac{x^2}{x^5 + y^2 + z^2}.$$

Taking the cyclic sum, we have

$$\sum_{\text{cyclic}} \frac{x^2(yz + y^2 + z^2)}{(x^2 + y^2 + z^2)^2} \geq \sum_{\text{cyclic}} \frac{x^2}{x^5 + y^2 + z^2}.$$

Our job is now to establish the following homogeneous inequality

$$1 \geq \sum_{\text{cyclic}} \frac{x^2(yz + y^2 + z^2)}{(x^2 + y^2 + z^2)^2} \Leftrightarrow (x^2 + y^2 + z^2)^2 \geq 2 \sum_{\text{cyclic}} x^2y^2 + \sum_{\text{cyclic}} x^2yz \Leftrightarrow \sum_{\text{cyclic}} x^4 \geq \sum_{\text{cyclic}} x^2yz.$$

However, by the AM-GM inequality, we obtain

$$\sum_{\text{cyclic}} x^4 = \sum_{\text{cyclic}} \frac{x^4 + y^4}{2} \geq \sum_{\text{cyclic}} x^2y^2 = \sum_{\text{cyclic}} x^2 \left(\frac{y^2 + z^2}{2} \right) \geq \sum_{\text{cyclic}} x^2yz.$$

[Second Way] We claim that

$$\frac{2x^4 + y^4 + z^4 + 4x^2y^2 + 4x^2z^2}{4(x^2 + y^2 + z^2)^2} \geq \frac{x^2}{x^5 + y^2 + z^2}.$$

We do this by proving

$$\frac{2x^4 + y^4 + z^4 + 4x^2y^2 + 4x^2z^2}{4(x^2 + y^2 + z^2)^2} \geq \frac{x^2yz}{x^4 + y^3z + yz^3}$$

because $xyz \geq 1$ implies that

$$\frac{x^2yz}{x^4 + y^3z + yz^3} = \frac{x^2}{\frac{x^5}{xyz} + y^2 + z^2} \geq \frac{x^2}{x^5 + y^2 + z^2}.$$

Hence, we need to show the homogeneous inequality

$$(2x^4 + y^4 + z^4 + 4x^2y^2 + 4x^2z^2)(x^4 + y^3z + yz^3) \geq 4x^2yz(x^2 + y^2 + z^2)^2.$$

However, this is a straightforward consequence of the AM-GM inequality.

$$\begin{aligned} & (2x^4 + y^4 + z^4 + 4x^2y^2 + 4x^2z^2)(x^4 + y^3z + yz^3) - 4x^2yz(x^2 + y^2 + z^2)^2 \\ &= (x^8 + x^4y^4 + x^6y^2 + x^6y^2 + y^7z + y^3z^5) + (x^8 + x^4z^4 + x^6z^2 + x^6z^2 + yz^7 + y^5z^3) \\ & \quad + 2(x^6y^2 + x^6z^2) - 6x^4y^3z - 6x^4yz^3 - 2x^6yz \\ & \geq 6\sqrt[6]{x^8 \cdot x^4y^4 \cdot x^6y^2 \cdot x^6y^2 \cdot y^7z \cdot y^3z^5} + 6\sqrt[6]{x^8 \cdot x^4z^4 \cdot x^6z^2 \cdot x^6z^2 \cdot yz^7 \cdot y^5z^3} \\ & \quad + 2\sqrt{x^6y^2 \cdot x^6z^2} - 6x^4y^3z - 6x^4yz^3 - 2x^6yz \\ &= 0. \end{aligned}$$

Taking the cyclic sum, we obtain

$$1 = \sum_{\text{cyclic}} \frac{2x^4 + y^4 + z^4 + 4x^2y^2 + 4x^2z^2}{4(x^2 + y^2 + z^2)^2} \geq \sum_{\text{cyclic}} \frac{x^2}{x^5 + y^2 + z^2}.$$

□

Third Solution. (by an IMO 2005 contestant Iurie Boreico⁵ from Moldova) We establish that

$$\frac{x^5 - x^2}{x^5 + y^2 + z^2} \geq \frac{x^5 - x^2}{x^3(x^2 + y^2 + z^2)}.$$

It follows immediately from the identity

$$\frac{x^5 - x^2}{x^5 + y^2 + z^2} - \frac{x^5 - x^2}{x^3(x^2 + y^2 + z^2)} = \frac{(x^3 - 1)^2 x^2 (y^2 + z^2)}{x^3(x^2 + y^2 + z^2)(x^5 + y^2 + z^2)}.$$

Taking the cyclic sum and using $xyz \geq 1$, we have

$$\sum_{\text{cyclic}} \frac{x^5 - x^2}{x^5 + y^2 + z^2} \geq \frac{1}{x^5 + y^2 + z^2} \sum_{\text{cyclic}} \left(x^2 - \frac{1}{x} \right) \geq \frac{1}{x^5 + y^2 + z^2} \sum_{\text{cyclic}} (x^2 - yz) \geq 0.$$

□

Exercise 5. (USAMO Summer Program 2002) Let a, b, c be positive real numbers. Prove that

$$\left(\frac{2a}{b+c} \right)^{\frac{2}{3}} + \left(\frac{2b}{c+a} \right)^{\frac{2}{3}} + \left(\frac{2c}{a+b} \right)^{\frac{2}{3}} \geq 3.$$

(Hint. [TJM]) Establish the inequality $\left(\frac{2a}{b+c} \right)^{\frac{2}{3}} \geq 3 \left(\frac{a}{a+b+c} \right)$.

Exercise 6. (APMO 2005) ($abc = 8$, $a, b, c > 0$)

$$\frac{a^2}{\sqrt{(1+a^3)(1+b^3)}} + \frac{b^2}{\sqrt{(1+b^3)(1+c^3)}} + \frac{c^2}{\sqrt{(1+c^3)(1+a^3)}} \geq \frac{4}{3}$$

(Hint.) Use the inequality $\frac{1}{\sqrt{1+x^3}} \geq \frac{2}{2+x^2}$ to give a lower bound of the left hand side.

⁵He received the special prize for this solution.

Chapter 3

Homogenizations and Normalizations

Every Mathematician Has Only a Few Tricks. *A long time ago an older and well-known number theorist made some disparaging remarks about Paul Erdős's work. You admire Erdős's contributions to mathematics as much as I do, and I felt annoyed when the older mathematician flatly and definitively stated that all of Erdős's work could be reduced to a few tricks which Erdős repeatedly relied on in his proofs. What the number theorist did not realize is that other mathematicians, even the very best, also rely on a few tricks which they use over and over. Take Hilbert. The second volume of Hilbert's collected papers contains Hilbert's papers in invariant theory. I have made a point of reading some of these papers with care. It is sad to note that some of Hilbert's beautiful results have been completely forgotten. But on reading the proofs of Hilbert's striking and deep theorems in invariant theory, it was surprising to verify that Hilbert's proofs relied on the same few tricks. Even Hilbert had only a few tricks!* Gian-Carlo Rota, *Ten Lessons I Wish I Had Been Taught*, Notices of the AMS, January 1997

3.1 Homogenizations

Many inequality problems come with constraints such as $ab = 1$, $xyz = 1$, $x+y+z = 1$. A non-homogeneous symmetric inequality can be transformed into a homogeneous one. Then we apply two powerful theorems : Shur's inequality and Muirhead's theorem. We begin with a simple example.

Problem 18. (Hungary 1996) Let a and b be positive real numbers with $a+b=1$. Prove that

$$\frac{a^2}{a+1} + \frac{b^2}{b+1} \geq \frac{1}{3}.$$

Solution. Using the condition $a+b=1$, we can reduce the given inequality to homogeneous one, i. e.,

$$\frac{1}{3} \leq \frac{a^2}{(a+b)(a+(a+b))} + \frac{b^2}{(a+b)(b+(a+b))} \text{ or } a^2b + ab^2 \leq a^3 + b^3,$$

which follows from $(a^3+b^3)-(a^2b+ab^2) = (a-b)^2(a+b) \geq 0$. The equality holds if and only if $a=b=\frac{1}{2}$. \square

The above inequality $a^2b + ab^2 \leq a^3 + b^3$ can be generalized as following :

Theorem 3.1.1. Let a_1, a_2, b_1, b_2 be positive real numbers such that $a_1 + a_2 = b_1 + b_2$ and $\max(a_1, a_2) \geq \max(b_1, b_2)$. Let x and y be nonnegative real numbers. Then, we have $x^{a_1}y^{a_2} + x^{a_2}y^{a_1} \geq x^{b_1}y^{b_2} + x^{b_2}y^{b_1}$.

Proof. Without loss of generality, we can assume that $a_1 \geq a_2, b_1 \geq b_2, a_1 \geq b_1$. If x or y is zero, then it clearly holds. So, we assume that both x and y are nonzero. It follows from $a_1 + a_2 = b_1 + b_2$ that $a_1 - a_2 = (b_1 - a_2) + (b_2 - a_2)$. It's easy to check

$$\begin{aligned} x^{a_1}y^{a_2} + x^{a_2}y^{a_1} - x^{b_1}y^{b_2} - x^{b_2}y^{b_1} &= x^{a_2}y^{a_2} (x^{a_1-a_2} + y^{a_1-a_2} - x^{b_1-a_2}y^{b_2-a_2} - x^{b_2-a_2}y^{b_1-a_2}) \\ &= x^{a_2}y^{a_2} (x^{b_1-a_2} - y^{b_1-a_2}) (x^{b_2-a_2} - y^{b_2-a_2}) \\ &= \frac{1}{x^{a_2}y^{a_2}} (x^{b_1} - y^{b_1}) (x^{b_2} - y^{b_2}) \geq 0. \end{aligned}$$

\square

Remark 3.1.1. When does the equality hold in the theorem 8?

We now introduce two summation notations \sum_{cyclic} and \sum_{sym} . Let $P(x, y, z)$ be a three variables function of x, y, z . Let us define :

$$\sum_{\text{cyclic}} P(x, y, z) = P(x, y, z) + P(y, z, x) + P(z, x, y),$$

$$\sum_{\text{sym}} P(x, y, z) = P(x, y, z) + P(x, z, y) + P(y, x, z) + P(y, z, x) + P(z, x, y) + P(z, y, x).$$

For example, we know that

$$\sum_{\text{cyclic}} x^3 y = x^3 y + y^3 z + z^3 x, \quad \sum_{\text{sym}} x^3 = 2(x^3 + y^3 + z^3)$$

$$\sum_{\text{sym}} x^2 y = x^2 y + x^2 z + y^2 z + y^2 x + z^2 x + z^2 y, \quad \sum_{\text{sym}} x y z = 6 x y z.$$

Problem 19. (IMO 1984/1) Let x, y, z be nonnegative real numbers such that $x + y + z = 1$. Prove that $0 \leq xy + yz + zx - 2xyz \leq \frac{7}{27}$.

Second Solution. Using the condition $x + y + z = 1$, we reduce the given inequality to homogeneous one, i.e.,

$$0 \leq (xy + yz + zx)(x + y + z) - 2xyz \leq \frac{7}{27}(x + y + z)^3.$$

The left hand side inequality is trivial because it's equivalent to

$$0 \leq x y z + \sum_{\text{sym}} x^2 y.$$

The right hand side inequality simplifies to

$$7 \sum_{\text{cyclic}} x^3 + 15xyz - 6 \sum_{\text{sym}} x^2 y \geq 0.$$

In the view of

$$7 \sum_{\text{cyclic}} x^3 + 15xyz - 6 \sum_{\text{sym}} x^2 y = \left(2 \sum_{\text{cyclic}} x^3 - \sum_{\text{sym}} x^2 y \right) + 5 \left(3xyz + \sum_{\text{cyclic}} x^3 - \sum_{\text{sym}} x^2 y \right),$$

it's enough to show that

$$2 \sum_{\text{cyclic}} x^3 \geq \sum_{\text{sym}} x^2 y \quad \text{and} \quad 3xyz + \sum_{\text{cyclic}} x^3 \geq \sum_{\text{sym}} x^2 y.$$

We note that

$$2 \sum_{\text{cyclic}} x^3 - \sum_{\text{sym}} x^2 y = \sum_{\text{cyclic}} (x^3 + y^3) - \sum_{\text{cyclic}} (x^2 y + xy^2) = \sum_{\text{cyclic}} (x^3 + y^3 - x^2 y - xy^2) \geq 0.$$

The second inequality can be rewritten as

$$\sum_{\text{cyclic}} x(x - y)(x - z) \geq 0,$$

which is a particular case of Schur's theorem in the next section. \square

After homogenizing, sometimes we can find the *right* approach to see the inequalities:

(Iran 1998) Prove that, for all $x, y, z > 1$ such that $\frac{1}{x} + \frac{1}{y} + \frac{1}{z} = 2$,

$$\sqrt{x+y+z} \geq \sqrt{x-1} + \sqrt{y-1} + \sqrt{z-1}.$$

Second Solution. After the algebraic substitution $a = \frac{1}{x}$, $b = \frac{1}{y}$, $c = \frac{1}{z}$, we are required to prove that

$$\sqrt{\frac{1}{a} + \frac{1}{b} + \frac{1}{c}} \geq \sqrt{\frac{1-a}{a}} + \sqrt{\frac{1-b}{b}} + \sqrt{\frac{1-c}{c}},$$

where $a, b, c \in (0, 1)$ and $a+b+c = 2$. Using the constraint $a+b+c = 2$, we obtain a homogeneous inequality

$$\sqrt{\frac{1}{2}(a+b+c) \left(\frac{1}{a} + \frac{1}{b} + \frac{1}{c} \right)} \geq \sqrt{\frac{\frac{a+b+c}{2} - a}{a}} + \sqrt{\frac{\frac{a+b+c}{2} - b}{b}} + \sqrt{\frac{\frac{a+b+c}{2} - c}{c}}$$

or

$$\sqrt{(a+b+c) \left(\frac{1}{a} + \frac{1}{b} + \frac{1}{c} \right)} \geq \sqrt{\frac{b+c-a}{a}} + \sqrt{\frac{c+a-b}{b}} + \sqrt{\frac{a+b-c}{c}},$$

which immediately follows from the Cauchy-Schwarz inequality

$$\sqrt{[(b+c-a) + (c+a-b) + (a+b-c)] \left(\frac{1}{a} + \frac{1}{b} + \frac{1}{c} \right)} \geq \sqrt{\frac{b+c-a}{a}} + \sqrt{\frac{c+a-b}{b}} + \sqrt{\frac{a+b-c}{c}}.$$

□

3.2 Schur's Inequality and Muirhead's Theorem

Theorem 3.2.1. (Schur) Let x, y, z be nonnegative real numbers. For any $r > 0$, we have

$$\sum_{\text{cyclic}} x^r(x-y)(x-z) \geq 0.$$

Proof. Since the inequality is symmetric in the three variables, we may assume without loss of generality that $x \geq y \geq z$. Then the given inequality may be rewritten as

$$(x-y)[x^r(x-z) - y^r(y-z)] + z^r(x-z)(y-z) \geq 0,$$

and every term on the left-hand side is clearly nonnegative. \square

Remark 3.2.1. When does the equality hold in Schur's Inequality?

Exercise 7. Disprove the following proposition: For all $a, b, c, d \geq 0$ and $r > 0$, we have

$$a^r(a-b)(a-c)(a-d) + b^r(b-c)(b-d)(b-a) + c^r(c-a)(c-b)(c-d) + d^r(d-a)(d-b)(d-c) \geq 0.$$

The following special case of Schur's inequality is useful :

$$\sum_{\text{cyclic}} x(x-y)(x-z) \geq 0 \Leftrightarrow 3xyz + \sum_{\text{cyclic}} x^3 \geq \sum_{\text{sym}} x^2y \Leftrightarrow \sum_{\text{sym}} xyz + \sum_{\text{sym}} x^3 \geq 2 \sum_{\text{sym}} x^2y.$$

Corollary 3.2.1. Let x, y, z be nonnegative real numbers. Then, we have

$$3xyz + x^3 + y^3 + z^3 \geq 2 \left((xy)^{\frac{3}{2}} + (yz)^{\frac{3}{2}} + (zx)^{\frac{3}{2}} \right).$$

Proof. By Schur's inequality and the AM-GM inequality, we have

$$3xyz + \sum_{\text{cyclic}} x^3 \geq \sum_{\text{cyclic}} x^2y + xy^2 \geq \sum_{\text{cyclic}} 2(xy)^{\frac{3}{2}}.$$

\square

We now use Schur's inequality to give an alternative solution of

(APMO 2004/5) Prove that, for all positive real numbers a, b, c ,

$$(a^2 + 2)(b^2 + 2)(c^2 + 2) \geq 9(ab + bc + ca).$$

Second Solution. After expanding, it becomes

$$8 + (abc)^2 + 2 \sum_{\text{cyclic}} a^2b^2 + 4 \sum_{\text{cyclic}} a^2 \geq 9 \sum_{\text{cyclic}} ab.$$

From the inequality $(ab-1)^2 + (bc-1)^2 + (ca-1)^2 \geq 0$, we obtain

$$6 + 2 \sum_{\text{cyclic}} a^2b^2 \geq 4 \sum_{\text{cyclic}} ab.$$

Hence, it will be enough to show that

$$2 + (abc)^2 + 4 \sum_{\text{cyclic}} a^2 \geq 5 \sum_{\text{cyclic}} ab.$$

Since $3(a^2 + b^2 + c^2) \geq 3(ab + bc + ca)$, it will be enough to show that

$$2 + (abc)^2 + \sum_{\text{cyclic}} a^2 \geq 2 \sum_{\text{cyclic}} ab,$$

which is a particular case of the following result for $t = 1$. \square

Corollary 3.2.2. Let $t \in (0, 3]$. For all $a, b, c \geq 0$, we have

$$(3-t) + t(abc)^{\frac{2}{t}} + \sum_{\text{cyclic}} a^2 \geq 2 \sum_{\text{cyclic}} ab.$$

In particular, we obtain non-homogeneous inequalities

$$\begin{aligned} \frac{5}{2} + \frac{1}{2}(abc)^4 + a^2 + b^2 + c^2 &\geq 2(ab + bc + ca), \\ 2 + (abc)^2 + a^2 + b^2 + c^2 &\geq 2(ab + bc + ca), \\ 1 + 2abc + a^2 + b^2 + c^2 &\geq 2(ab + bc + ca). \end{aligned}$$

Proof. After setting $x = a^{\frac{2}{3}}$, $y = b^{\frac{2}{3}}$, $z = c^{\frac{2}{3}}$, it becomes

$$3 - t + t(xyz)^{\frac{3}{t}} + \sum_{\text{cyclic}} x^3 \geq 2 \sum_{\text{cyclic}} (xy)^{\frac{3}{2}}.$$

By the corollary 1, it will be enough to show that

$$3 - t + t(xyz)^{\frac{3}{t}} \geq 3xyz,$$

which is a straightforward consequence of the weighted AM-GM inequality :

$$\frac{3-t}{3} \cdot 1 + \frac{t}{3}(xyz)^{\frac{3}{t}} \geq 1^{\frac{3-t}{3}} \left((xyz)^{\frac{3}{t}} \right)^{\frac{t}{3}} = 3xyz.$$

One may check that the equality holds if and only if $a = b = c = 1$. \square

(IMO 2000/2) Let a, b, c be positive numbers such that $abc = 1$. Prove that

$$\left(a - 1 + \frac{1}{b} \right) \left(b - 1 + \frac{1}{c} \right) \left(c - 1 + \frac{1}{a} \right) \leq 1.$$

Second Solution. It is equivalent to the following homogeneous inequality¹ :

$$\left(a - (abc)^{1/3} + \frac{(abc)^{2/3}}{b} \right) \left(b - (abc)^{1/3} + \frac{(abc)^{2/3}}{c} \right) \left(c - (abc)^{1/3} + \frac{(abc)^{2/3}}{a} \right) \leq abc.$$

After the substitution $a = x^3, b = y^3, c = z^3$ with $x, y, z > 0$, it becomes

$$\left(x^3 - xyz + \frac{(xyz)^2}{y^3} \right) \left(y^3 - xyz + \frac{(xyz)^2}{z^3} \right) \left(z^3 - xyz + \frac{(xyz)^2}{x^3} \right) \leq x^3 y^3 z^3,$$

which simplifies to

$$(x^2y - y^2z + z^2x)(y^2z - z^2x + x^2y)(z^2x - x^2y + y^2z) \leq x^3y^3z^3$$

or

$$3x^3y^3z^3 + \sum_{\text{cyclic}} x^6y^3 \geq \sum_{\text{cyclic}} x^4y^4z + \sum_{\text{cyclic}} x^5y^2z^2$$

or

$$3(x^2y)(y^2z)(z^2x) + \sum_{\text{cyclic}} (x^2y)^3 \geq \sum_{\text{sym}} (x^2y)^2(y^2z)$$

which is a special case of Schur's inequality. \square

Here is another inequality problem with the constraint $abc = 1$.

¹For an alternative homogenization, see the problem 1 in the chapter 2.

Problem 20. (Tournament of Towns 1997) Let a, b, c be positive numbers such that $abc = 1$. Prove that

$$\frac{1}{a+b+1} + \frac{1}{b+c+1} + \frac{1}{c+a+1} \leq 1.$$

Solution. We can rewrite the given inequality as following :

$$\frac{1}{a+b+(abc)^{1/3}} + \frac{1}{b+c+(abc)^{1/3}} + \frac{1}{c+a+(abc)^{1/3}} \leq \frac{1}{(abc)^{1/3}}.$$

We make the substitution $a = x^3, b = y^3, c = z^3$ with $x, y, z > 0$. Then, it becomes

$$\frac{1}{x^3 + y^3 + xyz} + \frac{1}{y^3 + z^3 + xyz} + \frac{1}{z^3 + x^3 + xyz} \leq \frac{1}{xyz}$$

which is equivalent to

$$xyz \sum_{\text{cyclic}} (x^3 + y^3 + xyz)(y^3 + z^3 + xyz) \leq (x^3 + y^3 + xyz)(y^3 + z^3 + xyz)(z^3 + x^3 + xyz)$$

or

$$\sum_{\text{sym}} x^6 y^3 \geq \sum_{\text{sym}} x^5 y^2 z^2 \quad !$$

We apply the theorem 9 to obtain

$$\begin{aligned} \sum_{\text{sym}} x^6 y^3 &= \sum_{\text{cyclic}} x^6 y^3 + y^6 x^3 \\ &\geq \sum_{\text{cyclic}} x^5 y^4 + y^5 x^4 \\ &= \sum_{\text{cyclic}} x^5 (y^4 + z^4) \\ &\geq \sum_{\text{cyclic}} x^5 (y^2 z^2 + y^2 z^2) \\ &= \sum_{\text{sym}} x^5 y^2 z^2. \end{aligned}$$

□

Exercise 8. ([TZ], pp.142) Prove that for any acute triangle ABC ,

$$\cot^3 A + \cot^3 B + \cot^3 C + 6 \cot A \cot B \cot C \geq \cot A + \cot B + \cot C.$$

Exercise 9. (Korea 1998) Let I be the incenter of a triangle ABC . Prove that

$$IA^2 + IB^2 + IC^2 \geq \frac{BC^2 + CA^2 + AB^2}{3}.$$

Exercise 10. ([IN], pp.103) Let a, b, c be the lengths of a triangle. Prove that

$$a^2 b + a^2 c + b^2 c + b^2 a + c^2 a + c^2 b > a^3 + b^3 + c^3 + 2abc.$$

Exercise 11. (Surányi's inequality)) Show that, for all $x_1, \dots, x_n \geq 0$,

$$(n-1)(x_1^n + \dots + x_n^n) + nx_1 \dots x_n \geq (x_1 + \dots + x_n)(x_1^{n-1} + \dots + x_n^{n-1}).$$

Theorem 3.2.2. (Muirhead) Let $a_1, a_2, a_3, b_1, b_2, b_3$ be real numbers such that

$$a_1 \geq a_2 \geq a_3 \geq 0, b_1 \geq b_2 \geq b_3 \geq 0, a_1 \geq b_1, a_1 + a_2 \geq b_1 + b_2, a_1 + a_2 + a_3 = b_1 + b_2 + b_3.$$

Let x, y, z be positive real numbers. Then, we have $\sum_{\text{sym}} x^{a_1} y^{a_2} z^{a_3} \geq \sum_{\text{sym}} x^{b_1} y^{b_2} z^{b_3}$.

Proof. Case 1. $b_1 \geq a_2$: It follows from $a_1 \geq a_1 + a_2 - b_1$ and from $a_1 \geq b_1$ that $a_1 \geq \max(a_1 + a_2 - b_1, b_1)$ so that $\max(a_1, a_2) = a_1 \geq \max(a_1 + a_2 - b_1, b_1)$. From $a_1 + a_2 - b_1 \geq b_1 + a_3 - b_1 = a_3$ and $a_1 + a_2 - b_1 \geq b_2 \geq b_3$, we have $\max(a_1 + a_2 - b_1, a_3) \geq \max(b_2, b_3)$. Apply the theorem 8 twice to obtain

$$\begin{aligned} \sum_{\text{sym}} x^{a_1} y^{a_2} z^{a_3} &= \sum_{\text{cyclic}} z^{a_3} (x^{a_1} y^{a_2} + x^{a_2} y^{a_1}) \\ &\geq \sum_{\text{cyclic}} z^{a_3} (x^{a_1+a_2-b_1} y^{b_1} + x^{b_1} y^{a_1+a_2-b_1}) \\ &= \sum_{\text{cyclic}} x^{b_1} (y^{a_1+a_2-b_1} z^{a_3} + y^{a_3} z^{a_1+a_2-b_1}) \\ &\geq \sum_{\text{cyclic}} x^{b_1} (y^{b_2} z^{b_3} + y^{b_3} z^{b_2}) \\ &= \sum_{\text{sym}} x^{b_1} y^{b_2} z^{b_3}. \end{aligned}$$

Case 2. $b_1 \leq a_2$: It follows from $3b_1 \geq b_1 + b_2 + b_3 = a_1 + a_2 + a_3 \geq b_1 + a_2 + a_3$ that $b_1 \geq a_2 + a_3 - b_1$ and that $a_1 \geq a_2 \geq b_1 \geq a_2 + a_3 - b_1$. Therefore, we have $\max(a_2, a_3) \geq \max(b_1, a_2 + a_3 - b_1)$ and $\max(a_1, a_2 + a_3 - b_1) \geq \max(b_2, b_3)$. Apply the theorem 8 twice to obtain

$$\begin{aligned} \sum_{\text{sym}} x^{a_1} y^{a_2} z^{a_3} &= \sum_{\text{cyclic}} x^{a_1} (y^{a_2} z^{a_3} + y^{a_3} z^{a_2}) \\ &\geq \sum_{\text{cyclic}} x^{a_1} (y^{b_1} z^{a_2+a_3-b_1} + y^{a_2+a_3-b_1} z^{b_1}) \\ &= \sum_{\text{cyclic}} y^{b_1} (x^{a_1} z^{a_2+a_3-b_1} + x^{a_2+a_3-b_1} z^{a_1}) \\ &\geq \sum_{\text{cyclic}} y^{b_1} (x^{b_2} z^{b_3} + x^{b_3} z^{b_2}) \\ &= \sum_{\text{sym}} x^{b_1} y^{b_2} z^{b_3}. \end{aligned}$$

□

Remark 3.2.2. The equality holds if and only if $x = y = z$. However, if we allow $x = 0$ or $y = 0$ or $z = 0$, then one may easily check that the equality holds when $a_1, a_2, a_3 > 0$ and $b_1, b_2, b_3 > 0$ if and only if

$$x = y = z \text{ or } x = y, z = 0 \text{ or } y = z, x = 0 \text{ or } z = x, y = 0.$$

We can use Muirhead's theorem to prove Nesbitt's inequality.

(Nesbitt) For all positive real numbers a, b, c , we have

$$\frac{a}{b+c} + \frac{b}{c+a} + \frac{c}{a+b} \geq \frac{3}{2}.$$

Proof 6. Clearing the denominators of the inequality, it becomes

$$2 \sum_{\text{cyclic}} a(a+b)(a+c) \geq 3(a+b)(b+c)(c+a) \text{ or } \sum_{\text{sym}} a^3 \geq \sum_{\text{sym}} a^2 b.$$

(IMO 1995) Let a, b, c be positive numbers such that $abc = 1$. Prove that

$$\frac{1}{a^3(b+c)} + \frac{1}{b^3(c+a)} + \frac{1}{c^3(a+b)} \geq \frac{3}{2}.$$

Second Solution. It's equivalent to

$$\frac{1}{a^3(b+c)} + \frac{1}{b^3(c+a)} + \frac{1}{c^3(a+b)} \geq \frac{3}{2(abc)^{4/3}}.$$

Set $a = x^3, b = y^3, c = z^3$ with $x, y, z > 0$. Then, it becomes $\sum_{\text{cyclic}} \frac{1}{x^9(y^3+z^3)} \geq \frac{3}{2x^4y^4z^4}$. Clearing denominators, this becomes

$$\sum_{\text{sym}} x^{12}y^{12} + 2 \sum_{\text{sym}} x^{12}y^9z^3 + \sum_{\text{sym}} x^9y^9z^6 \geq 3 \sum_{\text{sym}} x^{11}y^8z^5 + 6x^8y^8z^8$$

or

$$\left(\sum_{\text{sym}} x^{12}y^{12} - \sum_{\text{sym}} x^{11}y^8z^5 \right) + 2 \left(\sum_{\text{sym}} x^{12}y^9z^3 - \sum_{\text{sym}} x^{11}y^8z^5 \right) + \left(\sum_{\text{sym}} x^9y^9z^6 - \sum_{\text{sym}} x^8y^8z^8 \right) \geq 0,$$

and every term on the left hand side is nonnegative by Muirhead's theorem. \square

Problem 21. (Iran 1996) Let x, y, z be positive real numbers. Prove that

$$(xy + yz + zx) \left(\frac{1}{(x+y)^2} + \frac{1}{(y+z)^2} + \frac{1}{(z+x)^2} \right) \geq \frac{9}{4}.$$

Proof. It's equivalent to

$$4 \sum_{\text{sym}} x^5y + 2 \sum_{\text{cyclic}} x^4yz + 6x^2y^2z^2 - \sum_{\text{sym}} x^4y^2 - 6 \sum_{\text{cyclic}} x^3y^3 - 2 \sum_{\text{sym}} x^3y^2z \geq 0.$$

We rewrite this as following

$$\left(\sum_{\text{sym}} x^5y - \sum_{\text{sym}} x^4y^2 \right) + 3 \left(\sum_{\text{sym}} x^5y - \sum_{\text{sym}} x^3y^3 \right) + 2xyz \left(3xyz + \sum_{\text{cyclic}} x^3 - \sum_{\text{sym}} x^2y \right) \geq 0.$$

By Muirhead's theorem and Schur's inequality, it's a sum of three nonnegative terms. \square

Problem 22. Let x, y, z be nonnegative real numbers with $xy + yz + zx = 1$. Prove that

$$\frac{1}{x+y} + \frac{1}{y+z} + \frac{1}{z+x} \geq \frac{5}{2}.$$

Proof. Using $xy + yz + zx = 1$, we homogenize the given inequality as following :

$$(xy + yz + zx) \left(\frac{1}{x+y} + \frac{1}{y+z} + \frac{1}{z+x} \right)^2 \geq \left(\frac{5}{2} \right)^2$$

or

$$4 \sum_{\text{sym}} x^5y + \sum_{\text{sym}} x^4yz + 14 \sum_{\text{sym}} x^3y^2z + 38x^2y^2z^2 \geq \sum_{\text{sym}} x^4y^2 + 3 \sum_{\text{sym}} x^3y^3$$

or

$$\left(\sum_{\text{sym}} x^5y - \sum_{\text{sym}} x^4y^2 \right) + 3 \left(\sum_{\text{sym}} x^5y - \sum_{\text{sym}} x^3y^3 \right) + xyz \left(\sum_{\text{sym}} x^3 + 14 \sum_{\text{sym}} x^2y + 38xyz \right) \geq 0.$$

By Muirhead's theorem, we get the result. In the above inequality, without the condition $xy + yz + zx = 1$, the equality holds if and only if $x = y, z = 0$ or $y = z, x = 0$ or $z = x, y = 0$. Since $xy + yz + zx = 1$, the equality occurs when $(x, y, z) = (1, 1, 0), (1, 0, 1), (0, 1, 1)$. \square

3.3 Normalizations

In the previous sections, we transformed non-homogeneous inequalities into homogeneous ones. On the other hand, homogeneous inequalities also can be normalized in *various* ways. We offer two alternative solutions of the problem 8 by normalizations :

(IMO 2001/2) Let a, b, c be positive real numbers. Prove that

$$\frac{a}{\sqrt{a^2 + 8bc}} + \frac{b}{\sqrt{b^2 + 8ca}} + \frac{c}{\sqrt{c^2 + 8ab}} \geq 1.$$

Third Solution. We make the substitution $x = \frac{a}{a+b+c}$, $y = \frac{b}{a+b+c}$, $z = \frac{c}{a+b+c}$.² The problem is

$$xf(x^2 + 8yz) + yf(y^2 + 8zx) + zf(z^2 + 8xy) \geq 1,$$

where $f(t) = \frac{1}{\sqrt{t}}$. Since f is convex on \mathbb{R}^+ and $x + y + z = 1$, we apply (the weighted) Jensen's inequality to obtain

$$xf(x^2 + 8yz) + yf(y^2 + 8zx) + zf(z^2 + 8xy) \geq f(x(x^2 + 8yz) + y(y^2 + 8zx) + z(z^2 + 8xy)).$$

Note that $f(1) = 1$. Since the function f is strictly decreasing, it suffices to show that

$$1 \geq x(x^2 + 8yz) + y(y^2 + 8zx) + z(z^2 + 8xy).$$

Using $x + y + z = 1$, we homogenize it as $(x + y + z)^3 \geq x(x^2 + 8yz) + y(y^2 + 8zx) + z(z^2 + 8xy)$. However, this is easily seen from

$$(x + y + z)^3 - x(x^2 + 8yz) - y(y^2 + 8zx) - z(z^2 + 8xy) = 3[x(y - z)^2 + y(z - x)^2 + z(x - y)^2] \geq 0.$$

□

In the above solution, we normalized to $x + y + z = 1$. We now prove it by normalizing to $xyz = 1$.

Fourth Solution. We make the substitution $x = \frac{bc}{a^2}$, $y = \frac{ca}{b^2}$, $z = \frac{ab}{c^2}$. Then, we get $xyz = 1$ and the inequality becomes

$$\frac{1}{\sqrt{1+8x}} + \frac{1}{\sqrt{1+8y}} + \frac{1}{\sqrt{1+8z}} \geq 1$$

which is equivalent to

$$\sum_{\text{cyclic}} \sqrt{(1+8x)(1+8y)} \geq \sqrt{(1+8x)(1+8y)(1+8z)}.$$

After squaring both sides, it's equivalent to

$$8(x + y + z) + 2\sqrt{(1+8x)(1+8y)(1+8z)} \sum_{\text{cyclic}} \sqrt{1+8x} \geq 510.$$

Recall that $xyz = 1$. The AM-GM inequality gives us $x + y + z \geq 3$,

$$(1+8x)(1+8y)(1+8z) \geq 9x^{\frac{8}{9}} \cdot 9y^{\frac{8}{9}} \cdot 9z^{\frac{8}{9}} = 729 \text{ and } \sum_{\text{cyclic}} \sqrt{1+8x} \geq \sum_{\text{cyclic}} \sqrt{9x^{\frac{8}{9}}} \geq 9(xyz)^{\frac{4}{27}} = 9.$$

Using these three inequalities, we get the result. □

(IMO 1983/6) Let a, b, c be the lengths of the sides of a triangle. Prove that

$$a^2b(a-b) + b^2c(b-c) + c^2a(c-a) \geq 0.$$

²Dividing by $a + b + c$ gives the equivalent inequality $\sum_{\text{cyclic}} \frac{\frac{a}{a+b+c}}{\sqrt{\frac{a^2}{(a+b+c)^2} + \frac{8bc}{(a+b+c)^2}}} \geq 1$.

Second Solution. After setting $a = y + z$, $b = z + x$, $c = x + y$ for $x, y, z > 0$, it becomes

$$x^3z + y^3x + z^3y \geq x^2yz + xy^2z + xyz^2 \text{ or } \frac{x^2}{y} + \frac{y^2}{z} + \frac{z^2}{x} \geq x + y + z.$$

Since it's homogeneous, we can restrict our attention to the case $x + y + z = 1$. Then, it becomes

$$yf\left(\frac{x}{y}\right) + zf\left(\frac{y}{z}\right) + xf\left(\frac{z}{x}\right) \geq 1,$$

where $f(t) = t^2$. Since f is convex on \mathbb{R} , we apply (the weighted) Jensen's inequality to obtain

$$yf\left(\frac{x}{y}\right) + zf\left(\frac{y}{z}\right) + xf\left(\frac{z}{x}\right) \geq f\left(y \cdot \frac{x}{y} + z \cdot \frac{y}{z} + x \cdot \frac{z}{x}\right) = f(1) = 1.$$

□

Problem 23. (KMO Winter Program Test 2001) Prove that, for all $a, b, c > 0$,

$$\sqrt{(a^2b + b^2c + c^2a)(ab^2 + bc^2 + ca^2)} \geq abc + \sqrt[3]{(a^3 + abc)(b^3 + abc)(c^3 + abc)}$$

First Solution. Dividing by abc , it becomes

$$\sqrt{\left(\frac{a}{c} + \frac{b}{a} + \frac{c}{b}\right)\left(\frac{c}{a} + \frac{a}{b} + \frac{b}{c}\right)} \geq abc + \sqrt[3]{\left(\frac{a^2}{bc} + 1\right)\left(\frac{b^2}{ca} + 1\right)\left(\frac{c^2}{ab} + 1\right)}.$$

After the substitution $x = \frac{a}{b}$, $y = \frac{b}{c}$, $z = \frac{c}{a}$, we obtain the constraint $xyz = 1$. It takes the form

$$\sqrt{(x + y + z)(xy + yz + zx)} \geq 1 + \sqrt[3]{\left(\frac{x}{z} + 1\right)\left(\frac{y}{x} + 1\right)\left(\frac{z}{y} + 1\right)}.$$

From the constraint $xyz = 1$, we find two identities

$$\left(\frac{x}{z} + 1\right)\left(\frac{y}{x} + 1\right)\left(\frac{z}{y} + 1\right) = \left(\frac{x+z}{z}\right)\left(\frac{y+x}{x}\right)\left(\frac{z+y}{y}\right) = (z+x)(x+y)(y+z),$$

$$(x + y + z)(xy + yz + zx) = (x + y)(y + z)(z + x) + xyz = (x + y)(y + z)(z + x) + 1.$$

Letting $p = \sqrt[3]{(x + y)(y + z)(z + x)}$, the inequality now becomes $\sqrt{p^3 + 1} \geq 1 + p$. Applying the AM-GM inequality, we have $p \geq \sqrt[3]{2\sqrt{xy} \cdot 2\sqrt{yz} \cdot 2\sqrt{zx}} = 2$. It follows that $(p^3 + 1) - (1 + p)^2 = p(p + 1)(p - 2) \geq 0$. □

Problem 24. (IMO 1999/2) Let n be an integer with $n \geq 2$.

(a) Determine the least constant C such that the inequality

$$\sum_{1 \leq i < j \leq n} x_i x_j (x_i^2 + x_j^2) \leq C \left(\sum_{1 \leq i \leq n} x_i \right)^4$$

holds for all real numbers $x_1, \dots, x_n \geq 0$.

(b) For this constant C , determine when equality holds.

First Solution. (**Marcin E. Kuczma**³) For $x_1 = \dots = x_n = 0$, it holds for any $C \geq 0$. Hence, we consider the case when $x_1 + \dots + x_n > 0$. Since the inequality is homogeneous, we may normalize to $x_1 + \dots + x_n = 1$. We denote

$$F(x_1, \dots, x_n) = \sum_{1 \leq i < j \leq n} x_i x_j (x_i^2 + x_j^2).$$

³I slightly modified his solution in [Au99].

From the assumption $x_1 + \dots + x_n = 1$, we have

$$\begin{aligned} F(x_1, \dots, x_n) &= \sum_{1 \leq i < j \leq n} x_i^3 x_j + \sum_{1 \leq i < j \leq n} x_i x_j^3 = \sum_{1 \leq i \leq n} x_i^3 \sum_{j \neq i} x_i = \sum_{1 \leq i \leq n} x_i^3 (1 - x_i) \\ &= \sum_{i=1}^n x_i (x_i^2 - x_i^3). \end{aligned}$$

We claim that $C = \frac{1}{8}$. It suffices to show that

$$F(x_1, \dots, x_n) \leq \frac{1}{8} = F\left(\frac{1}{2}, \frac{1}{2}, 0, \dots, 0\right).$$

Lemma 3.3.1. $0 \leq x \leq y \leq \frac{1}{2}$ implies $x^2 - x^3 \leq y^2 - y^3$.

Proof. Since $x + y \leq 1$, we get $x + y \geq (x + y)^2 \geq x^2 + xy + y^2$. Since $y - x \geq 0$, this implies that $y^2 - x^2 \geq y^3 - x^3$ or $y^2 - y^3 \geq x^2 - x^3$, as desired. \square

Case 1. $\frac{1}{2} \geq x_1 \geq x_2 \geq \dots \geq x_n$

$$\sum_{i=1}^n x_i (x_i^2 - x_i^3) \leq \sum_{i=1}^n x_i \left(\left(\frac{1}{2}\right)^2 - \left(\frac{1}{2}\right)^3 \right) = \frac{1}{8} \sum_{i=1}^n x_i = \frac{1}{8}.$$

Case 2. $x_1 \geq \frac{1}{2} \geq x_2 \geq \dots \geq x_n$ Let $x_1 = x$ and $y = 1 - x = x_2 + \dots + x_n$. Since $y \geq x_2, \dots, x_n$,

$$F(x_1, \dots, x_n) = x^3 y + \sum_{i=2}^n x_i (x_i^2 - x_i^3) \leq x^3 y + \sum_{i=2}^n x_i (y^2 - y^3) = x^3 y + y(y^2 - y^3).$$

Since $x^3 y + y(y^2 - y^3) = x^3 y + y^3(1 - y) = xy(x^2 + y^2)$, it remains to show that

$$xy(x^2 + y^2) \leq \frac{1}{8}.$$

Using $x + y = 1$, we homogenize the above inequality as following.

$$xy(x^2 + y^2) \leq \frac{1}{8}(x + y)^4.$$

However, we immediately find that $(x + y)^4 - 8xy(x^2 + y^2) = (x - y)^4 \geq 0$.

\square

Exercise 12. (IMO unused 1991) Let n be a given integer with $n \geq 2$. Find the maximum value of

$$\sum_{1 \leq i < j \leq n} x_i x_j (x_i + x_j),$$

where $x_1, \dots, x_n \geq 0$ and $x_1 + \dots + x_n = 1$.

We close this section with another proofs of Nesbitt's inequality.

(Nesbitt) For all positive real numbers a, b, c , we have

$$\frac{a}{b+c} + \frac{b}{c+a} + \frac{c}{a+b} \geq \frac{3}{2}.$$

Proof 7. We may normalize to $a + b + c = 1$. Note that $0 < a, b, c < 1$. The problem is now to prove

$$\sum_{\text{cyclic}} \frac{a}{b+c} = \sum_{\text{cyclic}} f(a) \geq \frac{3}{2}, \text{ where } f(x) = \frac{x}{1-x}.$$

Since f is convex on $(0, 1)$, Jensen's inequality shows that

$$\frac{1}{3} \sum_{\text{cyclic}} f(a) \geq f\left(\frac{a+b+c}{3}\right) = f\left(\frac{1}{3}\right) = \frac{1}{2} \text{ or } \sum_{\text{cyclic}} f(a) \geq \frac{3}{2}.$$

Proof 8. (Cao Minh Quang) Assume that $a + b + c = 1$. Note that $ab + bc + ca \leq \frac{1}{3}(a + b + c)^2 = \frac{1}{3}$. More strongly, we establish that

$$\frac{a}{b+c} + \frac{b}{c+a} + \frac{c}{a+b} \geq 3 - \frac{9}{2}(ab + bc + ca)$$

or

$$\left(\frac{a}{b+c} + \frac{9a(b+c)}{4} \right) + \left(\frac{b}{c+a} + \frac{9b(c+a)}{4} \right) + \left(\frac{c}{a+b} + \frac{9c(a+b)}{4} \right) \geq 3.$$

The AM-GM inequality shows that

$$\sum_{\text{cyclic}} \frac{a}{b+c} + \frac{9a(b+c)}{4} \geq \sum_{\text{cyclic}} 2\sqrt{\frac{a}{b+c} \cdot \frac{9a(b+c)}{4}} = \sum_{\text{cyclic}} 3a = 3.$$

Proof 9. We now break the symmetry by a suitable normalization. Since the inequality is symmetric in the three variables, we may assume that $a \geq b \geq c$. After the substitution $x = \frac{a}{c}, y = \frac{b}{c}$, we have $x \geq y \geq 1$. It becomes

$$\frac{\frac{a}{c}}{\frac{b}{c} + 1} + \frac{\frac{b}{c}}{\frac{a}{c} + 1} + \frac{1}{\frac{a}{c} + \frac{b}{c}} \geq \frac{3}{2} \quad \text{or} \quad \frac{x}{y+1} + \frac{y}{x+1} \geq \frac{3}{2} - \frac{1}{x+y}.$$

We apply the AM-GM inequality to obtain

$$\frac{x+1}{y+1} + \frac{y+1}{x+1} \geq 2 \quad \text{or} \quad \frac{x}{y+1} + \frac{y}{x+1} \geq 2 - \frac{1}{y+1} + \frac{1}{x+1}.$$

It's enough to show that

$$2 - \frac{1}{y+1} + \frac{1}{x+1} \geq \frac{3}{2} - \frac{1}{x+y} \Leftrightarrow \frac{1}{2} - \frac{1}{y+1} \geq \frac{1}{x+1} - \frac{1}{x+y} \Leftrightarrow \frac{y-1}{2(1+y)} \geq \frac{y-1}{(x+1)(x+y)}.$$

However, the last inequality clearly holds for $x \geq y \geq 1$.

Proof 10. As in the previous proof, we may normalize to $c = 1$ with the assumption $a \geq b \geq 1$. We prove

$$\frac{a}{b+1} + \frac{b}{a+1} + \frac{1}{a+b} \geq \frac{3}{2}.$$

Let $A = a + b$ and $B = ab$. It becomes

$$\frac{a^2 + b^2 + a + b}{(a+1)(b+1)} + \frac{1}{a+b} \geq \frac{3}{2} \quad \text{or} \quad \frac{A^2 - 2B + A}{A+B+1} + \frac{1}{A} \geq \frac{3}{2} \quad \text{or} \quad 2A^3 - A^2 - A + 2 \geq B(7A - 2).$$

Since $7A - 2 > 2(a + b - 1) > 0$ and $A^2 = (a + b)^2 \geq 4ab = 4B$, it's enough to show that

$$4(2A^3 - A^2 - A + 2) \geq A^2(7A - 2) \Leftrightarrow A^3 - 2A^2 - 4A + 8 \geq 0.$$

However, it's easy to check that $A^3 - 2A^2 - 4A + 8 = (A - 2)^2(A + 2) \geq 0$.

3.4 Cauchy-Schwarz Inequality and Hölder's Inequality

We begin with the following famous theorem:

Theorem 3.4.1. (The Cauchy-Schwarz inequality) *Let $a_1, \dots, a_n, b_1, \dots, b_n$ be real numbers. Then,*

$$(a_1^2 + \dots + a_n^2)(b_1^2 + \dots + b_n^2) \geq (a_1 b_1 + \dots + a_n b_n)^2.$$

Proof. Let $A = \sqrt{a_1^2 + \dots + a_n^2}$ and $B = \sqrt{b_1^2 + \dots + b_n^2}$. In the case when $A = 0$, we get $a_1 = \dots = a_n = 0$. Thus, the given inequality clearly holds. So, we may assume that $A, B > 0$. We may normalize to

$$1 = a_1^2 + \dots + a_n^2 = b_1^2 + \dots + b_n^2.$$

Hence, we need to show that

$$|a_1 b_1 + \dots + a_n b_n| \leq 1.$$

We now apply the AM-GM inequality to deduce

$$|x_1 y_1 + \dots + x_n y_n| \leq |x_1 y_1| + \dots + |x_n y_n| \leq \frac{x_1^2 + y_1^2}{2} + \dots + \frac{x_n^2 + y_n^2}{2} = 1.$$

□

Exercise 13. *Prove the Lagrange identity :*

$$\left(\sum_{i=1}^n a_i^2 \right) \left(\sum_{i=1}^n b_i^2 \right) - \left(\sum_{i=1}^n a_i b_i \right)^2 = \sum_{1 \leq i < j \leq n} (a_i b_j - a_j b_i)^2.$$

Exercise 14. (Darij Grinberg) *Suppose that $0 < a_1 \leq \dots \leq a_n$ and $0 < b_1 \leq \dots \leq b_n$ be real numbers. Show that*

$$\frac{1}{4} \left(\sum_{k=1}^n a_k \right)^2 \left(\sum_{k=1}^n b_k \right)^2 > \left(\sum_{k=1}^n a_k^2 \right) \left(\sum_{k=1}^n b_k^2 \right) - \left(\sum_{k=1}^n a_k b_k \right)^2$$

Exercise 15. ([PF], S. S. Wagner) *Let $a_1, \dots, a_n, b_1, \dots, b_n$ be real numbers. Suppose that $x \in [0, 1]$. Show that*

$$\left(\sum_{i=1}^n a_i^2 + 2x \sum_{i < j} a_i a_j \right) \left(\sum_{i=1}^n b_i^2 + 2x \sum_{i < j} b_i b_j \right) \geq \left(\sum_{i=1}^n a_i b_i + x \sum_{i \leq j} a_i b_j \right)^2.$$

Exercise 16. *Let $a_1, \dots, a_n, b_1, \dots, b_n$ be real numbers. Show that*

$$\sqrt{(a_1 + \dots + a_n)(b_1 + \dots + b_n)} \geq \sqrt{a_1 b_1} + \dots + \sqrt{a_n b_n}.$$

Exercise 17. *Let $a_1, \dots, a_n, b_1, \dots, b_n$ be positive real numbers. Show that*

$$\frac{a_1^2}{b_1} + \dots + \frac{a_n^2}{b_n} \geq \frac{(a_1 + \dots + a_n)^2}{b_1 + \dots + b_n}.$$

Exercise 18. *Let $a_1, \dots, a_n, b_1, \dots, b_n$ be positive real numbers. Show that*

$$\frac{a_1}{b_1^2} + \dots + \frac{a_n}{b_n^2} \geq \frac{1}{a_1 + \dots + a_n} \left(\frac{a_1}{b_1} + \dots + \frac{a_n}{b_n} \right)^2.$$

Exercise 19. *Let $a_1, \dots, a_n, b_1, \dots, b_n$ be positive real numbers. Show that*

$$\frac{a_1}{b_1} + \dots + \frac{a_n}{b_n} \geq \frac{(a_1 + \dots + a_n)^2}{a_1 b_1 + \dots + a_n b_n}.$$

As an application of the Cauchy-Schwarz inequality, we give a different solution of the following problem.

(Iran 1998) Prove that, for all $x, y, z > 1$ such that $\frac{1}{x} + \frac{1}{y} + \frac{1}{z} = 2$,

$$\sqrt{x+y+z} \geq \sqrt{x-1} + \sqrt{y-1} + \sqrt{z-1}.$$

Third Solution. We note that $\frac{x-1}{x} + \frac{y-1}{y} + \frac{z-1}{z} = 1$. Apply the Cauchy-Schwarz inequality to deduce

$$\sqrt{x+y+z} = \sqrt{(x+y+z) \left(\frac{x-1}{x} + \frac{y-1}{y} + \frac{z-1}{z} \right)} \geq \sqrt{x-1} + \sqrt{y-1} + \sqrt{z-1}.$$

□

We now apply the Cauchy-Schwarz inequality to prove Nesbitt's inequality.

(Nesbitt) For all positive real numbers a, b, c , we have

$$\frac{a}{b+c} + \frac{b}{c+a} + \frac{c}{a+b} \geq \frac{3}{2}.$$

Proof 11. *Applying the Cauchy-Schwarz inequality, we have*

$$((b+c) + (c+a) + (a+b)) \left(\frac{1}{b+c} + \frac{1}{c+a} + \frac{1}{a+b} \right) \geq 3^2.$$

It follows that

$$\frac{a+b+c}{b+c} + \frac{a+b+c}{c+a} + \frac{a+b+c}{a+b} \geq \frac{9}{2} \quad \text{or} \quad 3 + \sum_{\text{cyclic}} \frac{a}{b+c} \geq \frac{9}{2}.$$

Proof 12. *The Cauchy-Schwarz inequality yields*

$$\sum_{\text{cyclic}} \frac{a}{b+c} \sum_{\text{cyclic}} a(b+c) \geq \left(\sum_{\text{cyclic}} a \right)^2 \quad \text{or} \quad \sum_{\text{cyclic}} \frac{a}{b+c} \geq \frac{(a+b+c)^2}{2(ab+bc+ca)} \geq \frac{3}{2}.$$

Problem 25. (Gazeta Matematică) *Prove that, for all $a, b, c > 0$,*

$$\sqrt{a^4 + a^2b^2 + b^4} + \sqrt{b^4 + b^2c^2 + c^4} + \sqrt{c^4 + c^2a^2 + a^4} \geq a\sqrt{2a^2 + bc} + b\sqrt{2b^2 + ca} + c\sqrt{2c^2 + ab}.$$

Solution. We obtain the chain of equalities and inequalities

$$\begin{aligned} \sum_{\text{cyclic}} \sqrt{a^4 + a^2b^2 + b^4} &= \sum_{\text{cyclic}} \sqrt{\left(a^4 + \frac{a^2b^2}{2} \right) + \left(b^4 + \frac{a^2b^2}{2} \right)} \\ &\geq \frac{1}{\sqrt{2}} \sum_{\text{cyclic}} \left(\sqrt{a^4 + \frac{a^2b^2}{2}} + \sqrt{b^4 + \frac{a^2b^2}{2}} \right) \quad (\text{Cauchy - Schwarz}) \\ &= \frac{1}{\sqrt{2}} \sum_{\text{cyclic}} \left(\sqrt{a^4 + \frac{a^2b^2}{2}} + \sqrt{a^4 + \frac{a^2c^2}{2}} \right) \\ &\geq \sqrt{2} \sum_{\text{cyclic}} \sqrt[4]{\left(a^4 + \frac{a^2b^2}{2} \right) \left(a^4 + \frac{a^2c^2}{2} \right)} \quad (\text{AM - GM}) \\ &\geq \sqrt{2} \sum_{\text{cyclic}} \sqrt{a^4 + \frac{a^2bc}{2}} \quad (\text{Cauchy - Schwarz}) \\ &= \sum_{\text{cyclic}} \sqrt{2a^4 + a^2bc}. \end{aligned}$$

□

Here is an ingenious solution of

(KMO Winter Program Test 2001) Prove that, for all $a, b, c > 0$,

$$\sqrt{(a^2b + b^2c + c^2a)(ab^2 + bc^2 + ca^2)} \geq abc + \sqrt[3]{(a^3 + abc)(b^3 + abc)(c^3 + abc)}$$

Second Solution. (based on work by an winter program participant) We obtain

$$\begin{aligned} & \sqrt{(a^2b + b^2c + c^2a)(ab^2 + bc^2 + ca^2)} \\ = & \frac{1}{2} \sqrt{[b(a^2 + bc) + c(b^2 + ca) + a(c^2 + ab)][c(a^2 + bc) + a(b^2 + ca) + b(c^2 + ab)]} \\ \geq & \frac{1}{2} (\sqrt{bc}(a^2 + bc) + \sqrt{ca}(b^2 + ca) + \sqrt{ab}(c^2 + ab)) \quad (\text{Cauchy - Schwarz}) \\ \geq & \frac{3}{2} \sqrt[3]{\sqrt{bc}(a^2 + bc) \cdot \sqrt{ca}(b^2 + ca) \cdot \sqrt{ab}(c^2 + ab)} \quad (\text{AM - GM}) \\ = & \frac{1}{2} \sqrt[3]{(a^3 + abc)(b^3 + abc)(c^3 + abc)} + \sqrt[3]{(a^3 + abc)(b^3 + abc)(c^3 + abc)} \\ \geq & \frac{1}{2} \sqrt[3]{2\sqrt{a^3 \cdot abc} \cdot 2\sqrt{b^3 \cdot abc} \cdot 2\sqrt{c^3 \cdot abc}} + \sqrt[3]{(a^3 + abc)(b^3 + abc)(c^3 + abc)} \quad (\text{AM - GM}) \\ = & abc + \sqrt[3]{(a^3 + abc)(b^3 + abc)(c^3 + abc)}. \end{aligned}$$

□

We now illustrate normalization techniques to establish classical theorems. Using the same idea in the proof of the Cauchy-Schwarz inequality, we find a natural generalization :

Theorem 3.4.2. Let a_{ij} ($i, j = 1, \dots, n$) be positive real numbers. Then, we have

$$(a_{11}^n + \dots + a_{1n}^n) \cdots (a_{n1}^n + \dots + a_{nn}^n) \geq (a_{11}a_{21} \cdots a_{n1} + \dots + a_{1n}a_{2n} \cdots a_{nn})^n.$$

Proof. Since the inequality is homogeneous, as in the proof of the theorem 11, we can normalize to

$$(a_{i1}^n + \dots + a_{in}^n)^{\frac{1}{n}} = 1 \text{ or } a_{i1}^n + \dots + a_{in}^n = 1 \quad (i = 1, \dots, n).$$

Then, the inequality takes the form $a_{11}a_{21} \cdots a_{n1} + \dots + a_{1n}a_{2n} \cdots a_{nn} \leq 1$ or $\sum_{i=1}^n a_{i1} \cdots a_{in} \leq 1$. Hence, it suffices to show that, for all $i = 1, \dots, n$,

$$a_{i1} \cdots a_{in} \leq \frac{1}{n}, \text{ where } a_{i1}^n + \dots + a_{in}^n = 1.$$

To finish the proof, it remains to show the following *homogeneous* inequality :

□

Theorem 3.4.3. (AM-GM inequality) Let a_1, \dots, a_n be positive real numbers. Then, we have

$$\frac{a_1 + \dots + a_n}{n} \geq \sqrt[n]{a_1 \cdots a_n}.$$

Proof. Since it's homogeneous, we may rescale a_1, \dots, a_n so that $a_1 \cdots a_n = 1$.⁴ We want to show that

$$a_1 \cdots a_n = 1 \implies a_1 + \dots + a_n \geq n.$$

The proof is by induction on n . If $n = 1$, it's trivial. If $n = 2$, then we get $a_1 + a_2 - 2 = a_1 + a_2 - 2\sqrt{a_1 a_2} = (\sqrt{a_1} - \sqrt{a_2})^2 \geq 0$. Now, we assume that it holds for some positive integer $n \geq 2$. And let a_1, \dots, a_{n+1} be positive numbers such that $a_1 \cdots a_n a_{n+1} = 1$. We may assume that $a_1 \geq 1 \geq a_2$. (Why?) It follows that $a_1 a_2 + 1 - a_1 - a_2 = (a_1 - 1)(a_2 - 1) \leq 0$ so that $a_1 a_2 + 1 \leq a_1 + a_2$. Since $(a_1 a_2) a_3 \cdots a_n = 1$, by the induction hypothesis, we have $a_1 a_2 + a_3 + \dots + a_{n+1} \geq n$. Hence, $a_1 + a_2 - 1 + a_3 + \dots + a_{n+1} \geq n$. □

The following simple observation is not tricky :

⁴Set $x_i = \frac{a_i}{(a_1 \cdots a_n)^{\frac{1}{n}}}$ ($i = 1, \dots, n$). Then, we get $x_1 \cdots x_n = 1$ and it becomes $x_1 + \dots + x_n \geq n$.

Let $a, b > 0$ and $m, n \in \mathbf{N}$. Take $x_1 = \dots = x_m = a$ and $x_{m+1} = \dots = x_{m+n} = b$. Applying the AM-GM inequality to $x_1, \dots, x_{m+n} > 0$, we obtain

$$\frac{ma + nb}{m+n} \geq (a^m b^n)^{\frac{1}{m+n}} \quad \text{or} \quad \frac{m}{m+n}a + \frac{n}{m+n}b \geq a^{\frac{m}{m+n}} b^{\frac{n}{m+n}}.$$

Hence, for all positive *rationals* ω_1 and ω_2 with $\omega_1 + \omega_2 = 1$, we get

$$\omega_1 a + \omega_2 b \geq a^{\omega_1} b^{\omega_2}.$$

We immediately have

Theorem 3.4.4. *Let $\omega_1, \omega_2 > 0$ with $\omega_1 + \omega_2 = 1$. For all $x, y > 0$, we have*

$$\omega_1 x + \omega_2 y \geq x^{\omega_1} y^{\omega_2}.$$

Proof. We can choose a positive *rational* sequence a_1, a_2, a_3, \dots such that

$$\lim_{n \rightarrow \infty} a_n = \omega_1.$$

And letting $b_i = 1 - a_i$, we get

$$\lim_{n \rightarrow \infty} b_n = \omega_2.$$

From the previous observation, we have

$$a_n x + b_n y \geq x^{a_n} y^{b_n}$$

By taking the limits to both sides, we get the result. \square

Modifying slightly the above arguments, we see that the AM-GM inequality implies that

Theorem 3.4.5. (Weighted AM-GM inequality) *Let $\omega_1, \dots, \omega_n > 0$ with $\omega_1 + \dots + \omega_n = 1$. For all $x_1, \dots, x_n > 0$, we have*

$$\omega_1 x_1 + \dots + \omega_n x_n \geq x_1^{\omega_1} \dots x_n^{\omega_n}.$$

Alternatively, we find that it is a straightforward consequence of the concavity of $\ln x$. Indeed, the weighted Jensen's inequality says that $\ln(\omega_1 x_1 + \dots + \omega_n x_n) \geq \omega_1 \ln(x_1) + \dots + \omega_n \ln(x_n) = \ln(x_1^{\omega_1} \dots x_n^{\omega_n})$.

Recall that the AM-GM inequality is used to deduce the theorem 18, which is a generalization of the Cauchy-Schwarz inequality. Since we now get the *weighted* version of the AM-GM inequality, we establish *weighted* version of the Cauchy-Schwarz inequality.

Theorem 3.4.6. (Hölder) *Let x_{ij} ($i = 1, \dots, m, j = 1, \dots, n$) be positive real numbers. Suppose that $\omega_1, \dots, \omega_n$ are positive real numbers satisfying $\omega_1 + \dots + \omega_n = 1$. Then, we have*

$$\prod_{j=1}^n \left(\sum_{i=1}^m x_{ij} \right)^{\omega_j} \geq \sum_{i=1}^m \left(\prod_{j=1}^n x_{ij}^{\omega_j} \right).$$

Proof. Because of the homogeneity of the inequality, as in the proof of the theorem 12, we may rescale x_{1j}, \dots, x_{mj} so that $x_{1j} + \dots + x_{mj} = 1$ for each $j \in \{1, \dots, n\}$. Then, we need to show that

$$\prod_{j=1}^n 1^{\omega_j} \geq \sum_{i=1}^m \prod_{j=1}^n x_{ij}^{\omega_j} \quad \text{or} \quad 1 \geq \sum_{i=1}^m \prod_{j=1}^n x_{ij}^{\omega_j}.$$

The weighted AM-GM inequality provides that

$$\sum_{j=1}^n \omega_j x_{ij} \geq \prod_{j=1}^n x_{ij}^{\omega_j} \quad (i \in \{1, \dots, m\}) \implies \sum_{i=1}^m \sum_{j=1}^n \omega_j x_{ij} \geq \sum_{i=1}^m \prod_{j=1}^n x_{ij}^{\omega_j}.$$

However, we immediately have

$$\sum_{i=1}^m \sum_{j=1}^n \omega_j x_{ij} = \sum_{j=1}^n \sum_{i=1}^m \omega_j x_{ij} = \sum_{j=1}^n \omega_j \left(\sum_{i=1}^m x_{ij} \right) = \sum_{j=1}^n \omega_j = 1.$$

\square

Chapter 4

Convexity

Any good idea can be stated in fifty words or less. S. M. Ulam

4.1 Jensen's Inequality

In the previous chapter, we deduced the weighted AM-GM inequality from the AM-GM inequality. We use the same idea to study the following functional inequalities.

Proposition 4.1.1. *Let $f : [a, b] \rightarrow \mathbb{R}$ be a **continuous** function. Then, the followings are equivalent.*

(1) *For all $n \in \mathbb{N}$, the following inequality holds.*

$$\omega_1 f(x_1) + \cdots + \omega_n f(x_n) \geq f(\omega_1 x_1 + \cdots + \omega_n x_n)$$

for all $x_1, \dots, x_n \in [a, b]$ and $\omega_1, \dots, \omega_n > 0$ with $\omega_1 + \cdots + \omega_n = 1$.

(2) *For all $n \in \mathbb{N}$, the following inequality holds.*

$$r_1 f(x_1) + \cdots + r_n f(x_n) \geq f(r_1 x_1 + \cdots + r_n x_n)$$

for all $x_1, \dots, x_n \in [a, b]$ and $r_1, \dots, r_n \in \mathbb{Q}^+$ with $r_1 + \cdots + r_n = 1$.

(3) *For all $N \in \mathbb{N}$, the following inequality holds.*

$$\frac{f(y_1) + \cdots + f(y_N)}{N} \geq f\left(\frac{y_1 + \cdots + y_N}{N}\right)$$

for all $y_1, \dots, y_N \in [a, b]$.

(4) *For all $k \in \{0, 1, 2, \dots\}$, the following inequality holds.*

$$\frac{f(y_1) + \cdots + f(y_{2^k})}{2^k} \geq f\left(\frac{y_1 + \cdots + y_{2^k}}{2^k}\right)$$

for all $y_1, \dots, y_{2^k} \in [a, b]$.

(5) *We have $\frac{1}{2}f(x) + \frac{1}{2}f(y) \geq f\left(\frac{x+y}{2}\right)$ for all $x, y \in [a, b]$.*

(6) *We have $\lambda f(x) + (1-\lambda)f(y) \geq f(\lambda x + (1-\lambda)y)$ for all $x, y \in [a, b]$ and $\lambda \in (0, 1)$.*

Proof. (1) \Rightarrow (2) \Rightarrow (3) \Rightarrow (4) \Rightarrow (5) is obvious.

(2) \Rightarrow (1) : Let $x_1, \dots, x_n \in [a, b]$ and $\omega_1, \dots, \omega_n > 0$ with $\omega_1 + \cdots + \omega_n = 1$. One may see that there exist positive rational sequences $\{r_k(1)\}_{k \in \mathbb{N}}, \dots, \{r_k(n)\}_{k \in \mathbb{N}}$ satisfying

$$\lim_{k \rightarrow \infty} r_k(j) = w_j \quad (1 \leq j \leq n) \quad \text{and} \quad r_k(1) + \cdots + r_k(n) = 1 \quad \text{for all } k \in \mathbb{N}.$$

By the hypothesis in (2), we obtain $r_k(1)f(x_1) + \cdots + r_k(n)f(x_n) \geq f(r_k(1)x_1 + \cdots + r_k(n)x_n)$. Since f is continuous, taking $k \rightarrow \infty$ to both sides yields the inequality

$$\omega_1 f(x_1) + \cdots + \omega_n f(x_n) \geq f(\omega_1 x_1 + \cdots + \omega_n x_n).$$

(3) \Rightarrow (2) : Let $x_1, \dots, x_n \in [a, b]$ and $r_1, \dots, r_n \in \mathbb{Q}^+$ with $r_1 + \dots + r_n = 1$. We can find a positive integer $N \in \mathbb{N}$ so that $Nr_1, \dots, Nr_n \in \mathbb{N}$. For each $i \in \{1, \dots, n\}$, we can write $r_i = \frac{p_i}{N}$, where $p_i \in \mathbb{N}$. It follows from $r_1 + \dots + r_n = 1$ that $N = p_1 + \dots + p_n$. Then, (3) implies that

$$\begin{aligned}
& r_1 f(x_1) + \dots + r_n f(x_n) \\
&= \overbrace{f(x_1) + \dots + f(x_1)}^{p_1 \text{ terms}} + \dots + \overbrace{f(x_n) + \dots + f(x_n)}^{p_n \text{ terms}} \\
&\geq f\left(\frac{\overbrace{x_1 + \dots + x_1}^{p_1 \text{ terms}} + \dots + \overbrace{x_n + \dots + x_n}^{p_n \text{ terms}}}{N}\right) \\
&= f(r_1 x_1 + \dots + r_n x_n).
\end{aligned}$$

(4) \Rightarrow (3) : Let $y_1, \dots, y_N \in [a, b]$. Take a large $k \in \mathbb{N}$ so that $2^k > N$. Let $a = \frac{y_1 + \dots + y_N}{N}$. Then, (4) implies that

$$\begin{aligned}
& \frac{f(y_1) + \dots + f(y_N) + (2^k - n)f(a)}{2^k} \\
&= \frac{f(y_1) + \dots + f(y_N) + \overbrace{f(a) + \dots + f(a)}^{(2^k - N) \text{ terms}}}{2^k} \\
&\geq f\left(\frac{y_1 + \dots + y_N + \overbrace{a + \dots + a}^{(2^k - N) \text{ terms}}}{2^k}\right) \\
&= f(a)
\end{aligned}$$

so that

$$f(y_1) + \dots + f(y_N) \geq Nf(a) = Nf\left(\frac{y_1 + \dots + y_N}{N}\right).$$

(5) \Rightarrow (4) : We use induction on k . In case $k = 0, 1, 2$, it clearly holds. Suppose that (4) holds for some $k \geq 2$. Let $y_1, \dots, y_{2^{k+1}} \in [a, b]$. By the induction hypothesis, we obtain

$$\begin{aligned}
& f(y_1) + \dots + f(y_{2^k}) + f(y_{2^k+1}) + \dots + f(y_{2^{k+1}}) \\
&\geq 2^k f\left(\frac{y_1 + \dots + y_{2^k}}{2^k}\right) + 2^k f\left(\frac{y_{2^k+1} + \dots + y_{2^{k+1}}}{2^k}\right) \\
&= 2^{k+1} \frac{f\left(\frac{y_1 + \dots + y_{2^k}}{2^k}\right) + f\left(\frac{y_{2^k+1} + \dots + y_{2^{k+1}}}{2^k}\right)}{2} \\
&\geq 2^{k+1} f\left(\frac{\frac{y_1 + \dots + y_{2^k}}{2^k} + \frac{y_{2^k+1} + \dots + y_{2^{k+1}}}{2^k}}{2}\right) \\
&= 2^{k+1} f\left(\frac{y_1 + \dots + y_{2^{k+1}}}{2^{k+1}}\right).
\end{aligned}$$

Hence, (4) holds for $k + 1$. This completes the induction.

So far, we've established that (1), (2), (3), (4), (5) are all equivalent. Since (1) \Rightarrow (6) \Rightarrow (5) is obvious, this completes the proof. \square

Definition 4.1.1. A real valued function f is said to be convex on $[a, b]$ if

$$\lambda f(x) + (1 - \lambda)f(y) \geq f(\lambda x + (1 - \lambda)y)$$

for all $x, y \in [a, b]$ and $\lambda \in (0, 1)$.

The above proposition says that

Corollary 4.1.1. (Jensen's inequality) *Let $f : [a, b] \rightarrow \mathbb{R}$ be a continuous convex function. For all $x_1, \dots, x_n \in [a, b]$, we have*

$$\frac{f(x_1) + \dots + f(x_n)}{n} \geq f\left(\frac{x_1 + \dots + x_n}{n}\right).$$

Corollary 4.1.2. (Weighted Jensen's inequality) *Let $f : [a, b] \rightarrow \mathbb{R}$ be a continuous convex function. Let $\omega_1, \dots, \omega_n > 0$ with $\omega_1 + \dots + \omega_n = 1$. For all $x_1, \dots, x_n \in [a, b]$, we have*

$$\omega_1 f(x_1) + \dots + \omega_n f(x_n) \geq f(\omega_1 x_1 + \dots + \omega_n x_n).$$

In fact, we can almost drop the continuity of f . As an exercise, show that every convex function on $[a, b]$ is continuous on (a, b) . So, every convex function on \mathbb{R} is continuous on \mathbb{R} . By the proposition again, we get

Corollary 4.1.3. (Convexity Criterion I) *Let $f : [a, b] \rightarrow \mathbb{R}$ be a continuous function. Suppose that*

$$\frac{f(x) + f(y)}{2} \geq f\left(\frac{x+y}{2}\right)$$

for all $x, y \in [a, b]$. Then, f is a convex function on $[a, b]$.

Exercise 20. (Convexity Criterion II) *Let $f : [a, b] \rightarrow \mathbb{R}$ be a continuous function which are differentiable twice in (a, b) . Show that the followings are equivalent.*

- (1) $f''(x) \geq 0$ for all $x \in (a, b)$.
- (2) f is convex on (a, b) .

When we deduce (5) \Rightarrow (4) \Rightarrow (3) \Rightarrow (2) in the proposition, we didn't use the continuity of f :

Corollary 4.1.4. *Let $f : [a, b] \rightarrow \mathbb{R}$ be a function. Suppose that*

$$\frac{f(x) + f(y)}{2} \geq f\left(\frac{x+y}{2}\right)$$

for all $x, y \in [a, b]$. Then, we have

$$r_1 f(x_1) + \dots + r_n f(x_n) \geq f(r_1 x_1 + \dots + r_n x_n)$$

for all $x_1, \dots, x_n \in [a, b]$ and $r_1, \dots, r_n \in \mathbb{Q}^+$ with $r_1 + \dots + r_n = 1$.

We close this section by presenting an well-known inductive proof of the weighted Jensen's inequality. It turns out that we can completely drop the continuity of f .

Second Proof. It clearly holds for $n = 1, 2$. We now assume that it holds for some $n \in \mathbb{N}$. Let $x_1, \dots, x_n, x_{n+1} \in [a, b]$ and $\omega_1, \dots, \omega_{n+1} > 0$ with $\omega_1 + \dots + \omega_{n+1} = 1$. Since $\frac{\omega_1}{1-\omega_{n+1}} + \dots + \frac{\omega_n}{1-\omega_{n+1}} = 1$, it follows from the induction hypothesis that

$$\begin{aligned} & \omega_1 f(x_1) + \dots + \omega_{n+1} f(x_{n+1}) \\ &= (1 - \omega_{n+1}) \left(\frac{\omega_1}{1 - \omega_{n+1}} f(x_1) + \dots + \frac{\omega_n}{1 - \omega_{n+1}} f(x_n) \right) + \omega_{n+1} f(x_{n+1}) \\ &\geq (1 - \omega_{n+1}) f \left(\frac{\omega_1}{1 - \omega_{n+1}} x_1 + \dots + \frac{\omega_n}{1 - \omega_{n+1}} x_n \right) + \omega_{n+1} f(x_{n+1}) \\ &\geq f \left((1 - \omega_{n+1}) \left[\frac{\omega_1}{1 - \omega_{n+1}} x_1 + \dots + \frac{\omega_n}{1 - \omega_{n+1}} x_n \right] + \omega_{n+1} x_{n+1} \right) \\ &= f(\omega_1 x_1 + \dots + \omega_{n+1} x_{n+1}). \end{aligned}$$

□

4.2 Power Means

Convexity is one of the most important concepts in analysis. Jensen's inequality is the most powerful tool in theory of inequalities. In this section, we shall establish the Power Mean inequality by applying Jensen's inequality in two ways. We begin with two simple lemmas.

Lemma 4.2.1. *Let a , b , and c be positive real numbers. Let us define a function $f : \mathbb{R} \rightarrow \mathbb{R}$ by*

$$f(x) = \ln \left(\frac{a^x + b^x + c^x}{3} \right),$$

where $x \in \mathbb{R}$. Then, we obtain $f'(0) = \ln(abc)^{\frac{1}{3}}$.

Proof. We compute $f'(x) = \frac{a^x \ln a + b^x \ln b + c^x \ln c}{a^x + b^x + c^x}$. Then, $f'(0) = \frac{\ln a + \ln b + \ln c}{3} = \ln(abc)^{\frac{1}{3}}$. \square

Lemma 4.2.2. *Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be a continuous function. Suppose that f is monotone increasing on $(0, \infty)$ and monotone increasing on $(-\infty, 0)$. Then, f is monotone increasing on \mathbb{R} .*

Proof. We first show that f is monotone increasing on $[0, \infty)$. By the hypothesis, it remains to show that $f(x) \geq f(0)$ for all $x > 0$. For all $\epsilon \in (0, x)$, we have $f(x) \geq f(\epsilon)$. Since f is continuous at 0, we obtain

$$f(x) \geq \lim_{\epsilon \rightarrow 0^+} f(\epsilon) = f(0).$$

Similarly, we find that f is monotone increasing on $(-\infty, 0]$. We now show that f is monotone increasing on \mathbb{R} . Let x and y be real numbers with $x > y$. We want to show that $f(x) \geq f(y)$. In case $0 \notin (x, y)$, we get the result by the hypothesis. In case $x \geq 0 \geq y$, it follows that $f(x) \geq f(0) \geq f(y)$. \square

Theorem 4.2.1. (Power Mean inequality for three variables) *Let a , b , and c be positive real numbers. We define a function $M_{(a,b,c)} : \mathbb{R} \rightarrow \mathbb{R}$ by*

$$M_{(a,b,c)}(0) = \sqrt[3]{abc}, \quad M_{(a,b,c)}(r) = \left(\frac{a^r + b^r + c^r}{3} \right)^{\frac{1}{r}} \quad (r \neq 0).$$

Then, $M_{(a,b,c)}$ is a monotone increasing continuous function.

First Proof. Write $M(r) = M_{(a,b,c)}(r)$. We first establish that M is continuous. Since M is continuous at r for all $r \neq 0$, it's enough to show that

$$\lim_{r \rightarrow 0} M(r) = \sqrt[3]{abc}.$$

Let $f(x) = \ln \left(\frac{a^x + b^x + c^x}{3} \right)$, where $x \in \mathbb{R}$. Since $f(0) = 0$, the lemma 2 implies that

$$\lim_{r \rightarrow 0} \frac{f(r)}{r} = \lim_{r \rightarrow 0} \frac{f(r) - f(0)}{r - 0} = f'(0) = \ln \sqrt[3]{abc}.$$

Since e^x is a continuous function, this means that

$$\lim_{r \rightarrow 0} M(r) = \lim_{r \rightarrow 0} e^{\frac{f(r)}{r}} = e^{\ln \sqrt[3]{abc}} = \sqrt[3]{abc}.$$

Now, we show that M is monotone increasing. By the lemma 3, it will be enough to establish that M is monotone increasing on $(0, \infty)$ and monotone increasing on $(-\infty, 0)$. We first show that M is monotone increasing on $(0, \infty)$. Let $x \geq y > 0$. We want to show that

$$\left(\frac{a^x + b^x + c^x}{3} \right)^{\frac{1}{x}} \geq \left(\frac{a^y + b^y + c^y}{3} \right)^{\frac{1}{y}}.$$

After the substitution $u = a^y$, $v = a^y$, $w = a^z$, it becomes

$$\left(\frac{u^{\frac{x}{y}} + v^{\frac{x}{y}} + w^{\frac{x}{y}}}{3} \right)^{\frac{1}{x}} \geq \left(\frac{u + v + w}{3} \right)^{\frac{1}{y}}.$$

Since it is homogeneous, we may normalize to $u + v + w = 3$. We are now required to show that

$$\frac{G(u) + G(v) + G(w)}{3} \geq 1,$$

where $G(t) = t^{\frac{x}{y}}$, where $t > 0$. Since $\frac{x}{y} \geq 1$, we find that G is convex. Jensen's inequality shows that

$$\frac{G(u) + G(v) + G(w)}{3} \geq G\left(\frac{u + v + w}{3}\right) = G(1) = 1.$$

Similarly, we may deduce that M is monotone increasing on $(-\infty, 0)$. \square

We've learned that the convexity of $f(x) = x^\lambda$ ($\lambda \geq 1$) implies the monotonicity of the power means. Now, we shall show that the convexity of $x \ln x$ also implies the power mean inequality.

Second Proof of the Monotonicity. Write $f(x) = M_{(a,b,c)}(x)$. We use the increasing function theorem. By the lemma 3, it's enough to show that $f'(x) \geq 0$ for all $x \neq 0$. Let $x \in \mathbb{R} - \{0\}$. We compute

$$\frac{f'(x)}{f(x)} = \frac{d}{dx} (\ln f(x)) = -\frac{1}{x^2} \ln \left(\frac{a^x + b^x + c^x}{3} \right) + \frac{1}{x} \frac{\frac{1}{3}(a^x \ln a + b^x \ln b + c^x \ln c)}{\frac{1}{3}(a^x + b^x + c^x)}$$

or

$$\frac{x^2 f'(x)}{f(x)} = -\ln \left(\frac{a^x + b^x + c^x}{3} \right) + \frac{a^x \ln a^x + b^x \ln b^x + c^x \ln c^x}{a^x + b^x + c^x}.$$

To establish $f'(x) \geq 0$, we now need to establish that

$$a^x \ln a^x + b^x \ln b^x + c^x \ln c^x \geq (a^x + b^x + c^x) \ln \left(\frac{a^x + b^x + c^x}{3} \right).$$

Let us introduce a function $f : (0, \infty) \rightarrow \mathbf{R}$ by $f(t) = t \ln t$, where $t > 0$. After the substitution $p = a^x$, $q = a^y$, $r = a^z$, it becomes

$$f(p) + f(q) + f(r) \geq 3f\left(\frac{p+q+r}{3}\right).$$

Since f is convex on $(0, \infty)$, it follows immediately from Jensen's inequality. \square

As a corollary, we obtain the RMS-AM-GM-HM inequality for three variables.

Corollary 4.2.1. *For all positive real numbers a , b , and c , we have*

$$\sqrt[3]{\frac{a^2 + b^2 + c^2}{3}} \geq \frac{a + b + c}{3} \geq \sqrt[3]{abc} \geq \frac{3}{\frac{1}{a} + \frac{1}{b} + \frac{1}{c}}.$$

Proof. The Power Mean inequality implies that $M_{(a,b,c)}(2) \geq M_{(a,b,c)}(1) \geq M_{(a,b,c)}(0) \geq M_{(a,b,c)}(-1)$. \square

Using the convexity of $x \ln x$ or the convexity of x^λ ($\lambda \geq 1$), we can also establish the monotonicity of the power means for n positive real numbers.

Theorem 4.2.2. (Power Mean inequality) *Let $x_1, \dots, x_n > 0$. The power mean of order r is defined by*

$$M_{(x_1, \dots, x_n)}(0) = \sqrt[n]{x_1 \cdots x_n}, \quad M_{(x_1, \dots, x_n)}(r) = \left(\frac{x_1^r + \cdots + x_n^r}{n} \right)^{\frac{1}{r}} \quad (r \neq 0).$$

Then, $M_{(x_1, \dots, x_n)} : \mathbb{R} \rightarrow \mathbb{R}$ is continuous and monotone increasing.

We conclude that

Corollary 4.2.2. (Geometric Mean as a Limit) *Let $x_1, \dots, x_n > 0$. Then,*

$$\sqrt[n]{x_1 \cdots x_n} = \lim_{r \rightarrow 0} \left(\frac{x_1^r + \cdots + x_n^r}{n} \right)^{\frac{1}{r}}.$$

Theorem 4.2.3. (RMS-AM-GM-HM inequality) *For all $x_1, \dots, x_n > 0$, we have*

$$\sqrt{\frac{x_1^2 + \cdots + x_n^2}{n}} \geq \frac{x_1 + \cdots + x_n}{n} \geq \sqrt[n]{x_1 \cdots x_n} \geq \frac{n}{\frac{1}{x_1} + \cdots + \frac{1}{x_n}}.$$

4.3 Majorization Inequality

We say that a vector $\mathbf{x} = (x_1, \dots, x_n)$ *majorizes* another vector $\mathbf{y} = (y_1, \dots, y_n)$ if

- (1) $x_1 \geq \dots \geq x_n, y_1 \geq \dots \geq y_n,$
- (2) $x_1 + \dots + x_k \geq y_1 + \dots + y_k$ for all $1 \leq k \leq n-1,$
- (3) $x_1 + \dots + x_n = y_1 + \dots + y_n.$

Theorem 4.3.1. (Majorization Inequality) *Let $f : [a, b] \rightarrow \mathbb{R}$ be a convex function. Suppose that (x_1, \dots, x_n) majorizes (y_1, \dots, y_n) , where $x_1, \dots, x_n, y_1, \dots, y_n \in [a, b]$. Then, we obtain*

$$f(x_1) + \dots + f(x_n) \geq f(y_1) + \dots + f(y_n).$$

For example, we can minimize $\cos A + \cos B + \cos C$, where ABC is an acute triangle. Recall that $-\cos x$ is convex on $(0, \frac{\pi}{2})$. Since $(\frac{\pi}{2}, \frac{\pi}{2}, 0)$ majorize (A, B, C) , the majorization inequality implies that

$$\cos A + \cos B + \cos C \geq \cos\left(\frac{\pi}{2}\right) + \cos\left(\frac{\pi}{2}\right) + \cos 0 = 1.$$

Also, in a triangle ABC , the convexity of $\tan^2(\frac{x}{4})$ on $[0, \pi]$ and the majorization inequality show that

$$21 - 12\sqrt{3} = 3 \tan^2\left(\frac{\pi}{12}\right) \leq \tan^2\left(\frac{A}{4}\right) + \tan^2\left(\frac{B}{4}\right) + \tan^2\left(\frac{C}{4}\right) \leq \tan^2\left(\frac{\pi}{4}\right) + \tan^2 0 + \tan^2 0 = 1.$$

(IMO 1999/2) Let n be an integer with $n \geq 2$.

Determine the least constant C such that the inequality

$$\sum_{1 \leq i < j \leq n} x_i x_j (x_i^2 + x_j^2) \leq C \left(\sum_{1 \leq i \leq n} x_i \right)^4$$

holds for all real numbers $x_1, \dots, x_n \geq 0$.

Second Solution. (**Kin Y. Li¹**) As in the first solution, after normalizing $x_1 + \dots + x_n = 1$, we maximize

$$\sum_{1 \leq i < j \leq n} x_i x_j (x_i^2 + x_j^2) = \sum_{i=1}^n f(x_i),$$

where $f(x) = x^3 - x^4$ is a convex function on $[0, \frac{1}{2}]$. Since the inequality is symmetric, we can restrict our attention to the case $x_1 \geq x_2 \geq \dots \geq x_n$. If $\frac{1}{2} \geq x_1$, then we see that $(\frac{1}{2}, \frac{1}{2}, 0, \dots, 0)$ majorizes (x_1, \dots, x_n) . Hence, the convexity of f on $[0, \frac{1}{2}]$ and the Majorization inequality show that

$$\sum_{i=1}^n f(x_i) \leq f\left(\frac{1}{2}\right) + f\left(\frac{1}{2}\right) + f(0) + \dots + f(0) = \frac{1}{8}.$$

We now consider the case when $\frac{1}{2} \geq x_1$. Write $x_1 = \frac{1}{2} - \epsilon$ for some $\epsilon \in [0, \frac{1}{2}]$. We find that $(1 - x_1, 0, \dots, 0)$ majorizes (x_2, \dots, x_n) . By the Majorization inequality, we find that

$$\sum_{i=2}^n f(x_i) \leq f(1 - x_1) + f(0) + \dots + f(0) = f(1 - x_1)$$

so that

$$\sum_{i=1}^n f(x_i) \leq f(x_1) + f(1 - x_1) = x_1(1 - x_1)[x_1^2 + (1 - x_1)^2] = \left(\frac{1}{4} - \epsilon^2\right) \left(\frac{1}{2} + 2\epsilon^2\right) = 2 \left(\frac{1}{16} - \epsilon^4\right) \leq \frac{1}{8}.$$

□

¹I slightly modified his solution in [KYL].

4.4 Supporting Line Inequality

There is a simple way to find new bounds for given differentiable functions. We begin to show that every supporting lines are tangent lines in the following sense.

Proposition 4.4.1. (Characterization of Supporting Lines) *Let f be a real valued function. Let $m, n \in \mathbb{R}$. Suppose that*

- (1) $f(\alpha) = m\alpha + n$ for some $\alpha \in \mathbb{R}$,
- (2) $f(x) \geq mx + n$ for all x in some interval (ϵ_1, ϵ_2) including α , and
- (3) f is differentiable at α .

Then, the supporting line $y = mx + n$ of f is the tangent line of f at $x = \alpha$.

Proof. Let us define a function $F : (\epsilon_1, \epsilon_2) \rightarrow \mathbb{R}$ by $F(x) = f(x) - mx - n$ for all $x \in (\epsilon_1, \epsilon_2)$. Then, F is differentiable at α and we obtain $F'(\alpha) = f'(\alpha) - m$. By the assumption (1) and (2), we see that F has a local minimum at α . So, the first derivative theorem for local extreme values implies that $0 = F'(\alpha) = f'(\alpha) - m$ so that $m = f'(\alpha)$ and that $n = f(\alpha) - m\alpha = f(\alpha) - f'(\alpha)\alpha$. It follows that $y = mx + n = f'(\alpha)(x - \alpha) + f(\alpha)$. \square

(Nesbitt, 1903) For all positive real numbers a, b, c , we have

$$\frac{a}{b+c} + \frac{b}{c+a} + \frac{c}{a+b} \geq \frac{3}{2}.$$

Proof 13. We may normalize to $a + b + c = 1$. Note that $0 < a, b, c < 1$. The problem is now to prove

$$\sum_{\text{cyclic}} f(a) \geq \frac{3}{2} \Leftrightarrow \frac{f(a) + f(b) + f(c)}{3} \geq f\left(\frac{1}{3}\right), \text{ where } f(x) = \frac{x}{1-x}.$$

The equation of the tangent line of f at $x = \frac{1}{3}$ is given by $y = \frac{9x-1}{4}$. We claim that $f(x) \geq \frac{9x-1}{4}$ for all $x \in (0, 1)$. It follows from the identity

$$f(x) - \frac{9x-1}{4} = \frac{(3x-1)^2}{4(1-x)}.$$

Now, we conclude that

$$\sum_{\text{cyclic}} \frac{a}{1-a} \geq \sum_{\text{cyclic}} \frac{9a-1}{4} = \frac{9}{4} \sum_{\text{cyclic}} a - \frac{3}{4} = \frac{3}{2}.$$

The above argument can be generalized. If a function f has a supporting line at some point on the graph of f , then f satisfies Jensen's inequality in the following sense.

Theorem 4.4.1. (Supporting Line Inequality) *Let $f : [a, b] \rightarrow \mathbb{R}$ be a function. Suppose that $\alpha \in [a, b]$ and $m \in \mathbb{R}$ satisfy*

$$f(x) \geq m(x - \alpha) + f(\alpha)$$

for all $x \in [a, b]$. Let $\omega_1, \dots, \omega_n > 0$ with $\omega_1 + \dots + \omega_n = 1$. Then, the following inequality holds

$$\omega_1 f(x_1) + \dots + \omega_n f(x_n) \geq f(\alpha)$$

for all $x_1, \dots, x_n \in [a, b]$ such that $\alpha = \omega_1 x_1 + \dots + \omega_n x_n$. In particular, we obtain

$$\frac{f(x_1) + \dots + f(x_n)}{n} \geq f\left(\frac{s}{n}\right),$$

where $x_1, \dots, x_n \in [a, b]$ with $x_1 + \dots + x_n = s$ for some $s \in [na, nb]$.

Proof. It follows that $\omega_1 f(x_1) + \dots + \omega_n f(x_n) \geq \omega_1 [m(x_1 - \alpha) + f(\alpha)] + \dots + \omega_n [m(x_n - \alpha) + f(\alpha)] = f(\alpha)$. \square

We can apply the supporting line inequality to deduce Jensen's inequality for differentiable functions.

Lemma 4.4.1. Let $f : (a, b) \rightarrow \mathbb{R}$ be a differentiable convex function. Let $y = l_\alpha(x)$ be the tangent line at $\alpha \in (a, b)$. Then, $f(x) \geq l_\alpha(x)$ for all $x \in (a, b)$.

Proof. Let $\alpha \in (a, b)$. We want to show that the tangent line $y = l_\alpha(x) = f'(\alpha)(x - \alpha) + f(\alpha)$ is the supporting line of f at $x = \alpha$ such that $f(x) \geq l_\alpha(x)$ for all $x \in (a, b)$. However, by Taylor's theorem, we can find a θ_x between α and x such that

$$f(x) = f(\alpha) + f'(\alpha)(x - \alpha) + \frac{f''(\theta_x)}{2}(x - \alpha)^2 \geq f(\alpha) + f'(\alpha)(x - \alpha).$$

□

(Weighted Jensen's inequality) Let $f : [a, b] \rightarrow \mathbb{R}$ be a continuous convex function which is differentiable twice on (a, b) . Let $\omega_1, \dots, \omega_n > 0$ with $\omega_1 + \dots + \omega_n = 1$. For all $x_1, \dots, x_n \in [a, b]$,

$$\omega_1 f(x_1) + \dots + \omega_n f(x_n) \geq f(\omega_1 x_1 + \dots + \omega_n x_n).$$

Third Proof. By the continuity of f , we may assume that $x_1, \dots, x_n \in (a, b)$. Now, let $\mu = \omega_1 x_1 + \dots + \omega_n x_n$. Then, $\mu \in (a, b)$. By the above lemma, f has the tangent line $y = l_\mu(x) = f'(\mu)(x - \mu) + f(\mu)$ at $x = \mu$ satisfying $f(x) \geq l_\mu(x)$ for all $x \in (a, b)$. Hence, the supporting line inequality shows that $\omega_1 f(x_1) + \dots + \omega_n f(x_n) \geq f(\mu) = f(\omega_1 x_1 + \dots + \omega_n x_n)$. □

We note that the cosine function is concave on $[0, \frac{\pi}{2}]$ and convex on $[\frac{\pi}{2}, \pi]$. Non-convex functions can be locally convex and have supporting lines at some points. This means that the supporting line inequality is a powerful tool because we can also produce Jensen-type inequalities for non-convex functions.

(Theorem 6) In any triangle ABC , we have $\cos A + \cos B + \cos C \leq \frac{3}{2}$.

Third Proof. Let $f(x) = -\cos x$. Our goal is to establish a three-variables inequality

$$\frac{f(A) + f(B) + f(C)}{3} \geq f\left(\frac{\pi}{3}\right),$$

where $A, B, C \in (0, \pi)$ with $A + B + C = \pi$. We compute $f'(x) = \sin x$. The equation of the tangent line of f at $x = \frac{\pi}{3}$ is given by $y = \frac{\sqrt{3}}{2}(x - \frac{\pi}{3}) - \frac{1}{2}$. To apply the supporting line inequality, we need to show that

$$-\cos x \geq \frac{\sqrt{3}}{2}\left(x - \frac{\pi}{3}\right) - \frac{1}{2}$$

for all $x \in (0, \pi)$. This is a one-variable inequality! We omit the proof. □

Problem 26. (Japan 1997) Let a, b , and c be positive real numbers. Prove that

$$\frac{(b+c-a)^2}{(b+c)^2+a^2} + \frac{(c+a-b)^2}{(c+a)^2+b^2} + \frac{(a+b-c)^2}{(a+b)^2+c^2} \geq \frac{3}{5}.$$

Proof. Because of the homogeneity of the inequality, we may normalize to $a + b + c = 1$. It takes the form

$$\frac{(1-2a)^2}{(1-a)^2+a^2} + \frac{(1-2b)^2}{(1-b)^2+b^2} + \frac{(1-2c)^2}{(1-c)^2+c^2} \geq \frac{3}{5} \Leftrightarrow \frac{1}{2a^2-2a+1} + \frac{1}{2b^2-2b+1} + \frac{1}{2c^2-2c+1} \leq \frac{27}{5}.$$

We find that the equation of the tangent line of $f(x) = \frac{1}{2x^2-2x+1}$ at $x = \frac{1}{3}$ is given by $y = \frac{54}{25}x + \frac{27}{25}$ and that

$$f(x) - \left(\frac{54}{25}x + \frac{27}{25}\right) = -\frac{2(3x-1)^2(6x+1)}{25(2x^2-2x+1)} \leq 0.$$

for all $x > 0$. It follows that

$$\sum_{\text{cyclic}} f(a) \leq \sum_{\text{cyclic}} \frac{54}{25}a + \frac{27}{25} = \frac{27}{5}.$$

□

Chapter 5

Problems, Problems, Problems

Each problem that I solved became a rule, which served afterwards to solve other problems. Rene Descartes

5.1 Multivariable Inequalities

M 1. (IMO short-listed 2003) Let (x_1, x_2, \dots, x_n) and (y_1, y_2, \dots, y_n) be two sequences of positive real numbers. Suppose that (z_1, z_2, \dots, z_n) is a sequence of positive real numbers such that

$$z_{i+j}^2 \geq x_i y_j$$

for all $1 \leq i, j \leq n$. Let $M = \max\{z_2, \dots, z_{2n}\}$. Prove that

$$\left(\frac{M + z_2 + \dots + z_{2n}}{2n} \right)^2 \geq \left(\frac{x_1 + \dots + x_n}{n} \right) \left(\frac{y_1 + \dots + y_n}{n} \right).$$

M 2. (Bosnia and Herzegovina 2002) Let $a_1, \dots, a_n, b_1, \dots, b_n, c_1, \dots, c_n$ be positive real numbers. Prove the following inequality :

$$\left(\sum_{i=1}^n a_i^3 \right) \left(\sum_{i=1}^n b_i^3 \right) \left(\sum_{i=1}^n c_i^3 \right) \geq \left(\sum_{i=1}^n a_i b_i c_i \right)^3.$$

M 3. (C¹2113, Marcin E. Kuczma) Prove that inequality

$$\sum_{i=1}^n a_i \sum_{i=1}^n b_i \geq \sum_{i=1}^n (a_i + b_i) \sum_{i=1}^n \frac{a_i b_i}{a_i + b_i}$$

for any positive real numbers $a_1, \dots, a_n, b_1, \dots, b_n$

M 4. (Yugoslavia 1998) Let $n > 1$ be a positive integer and $a_1, \dots, a_n, b_1, \dots, b_n$ be positive real numbers. Prove the following inequality.

$$\left(\sum_{i \neq j} a_i b_j \right)^2 \geq \sum_{i \neq j} a_i a_j \sum_{i \neq j} b_i b_j.$$

M 5. (C2176, Sefket Arslanagic) Prove that

$$((a_1 + b_1) \cdots (a_n + b_n))^{\frac{1}{n}} \geq (a_1 \cdots a_n)^{\frac{1}{n}} + (b_1 \cdots b_n)^{\frac{1}{n}}$$

where $a_1, \dots, a_n, b_1, \dots, b_n > 0$

¹CRUX with MAYHEM

M 6. (Korea 2001) Let x_1, \dots, x_n and y_1, \dots, y_n be real numbers satisfying

$$x_1^2 + \dots + x_n^2 = y_1^2 + \dots + y_n^2 = 1$$

Show that

$$2 \left| 1 - \sum_{i=1}^n x_i y_i \right| \geq (x_1 y_2 - x_2 y_1)^2$$

and determine when equality holds.

M 7. (Singapore 2001) Let $a_1, \dots, a_n, b_1, \dots, b_n$ be real numbers between 1001 and 2002 inclusive. Suppose that

$$\sum_{i=1}^n a_i^2 = \sum_{i=1}^n b_i^2.$$

Prove that

$$\sum_{i=1}^n \frac{a_i^3}{b_i} \leq \frac{17}{10} \sum_{i=1}^n a_i^2.$$

Determine when equality holds.

M 8. (Abel's inequality) Let $a_1, \dots, a_N, x_1, \dots, x_N$ be real numbers with $x_n \geq x_{n+1} > 0$ for all n . Show that

$$|a_1 x_1 + \dots + a_N x_N| \leq A x_1$$

where

$$A = \max\{|a_1|, |a_1 + a_2|, \dots, |a_1 + \dots + a_N|\}.$$

M 9. (China 1992) For every integer $n \geq 2$ find the smallest positive number $\lambda = \lambda(n)$ such that if

$$0 \leq a_1, \dots, a_n \leq \frac{1}{2}, \quad b_1, \dots, b_n > 0, \quad a_1 + \dots + a_n = b_1 + \dots + b_n = 1$$

then

$$b_1 \dots b_n \leq \lambda(a_1 b_1 + \dots + a_n b_n).$$

M 10. (C2551, Panos E. Tsaousoglou) Suppose that a_1, \dots, a_n are positive real numbers. Let $e_{j,k} = n-1$ if $j = k$ and $e_{j,k} = n-2$ otherwise. Let $d_{j,k} = 0$ if $j = k$ and $d_{j,k} = 1$ otherwise. Prove that

$$\sum_{j=1}^n \prod_{k=1}^n e_{j,k} a_k^2 \geq \prod_{j=1}^n \left(\sum_{k=1}^n d_{j,k} a_k \right)^2$$

M 11. (C2627, Walther Janous) Let $x_1, \dots, x_n (n \geq 2)$ be positive real numbers and let $x_1 + \dots + x_n$. Let a_1, \dots, a_n be non-negative real numbers. Determine the optimum constant $C(n)$ such that

$$\sum_{j=1}^n \frac{a_j (s_n - x_j)}{x_j} \geq C(n) \left(\prod_{j=1}^n a_j \right)^{\frac{1}{n}}.$$

M 12. (Hungary-Israel Binational Mathematical Competition 2000) Suppose that k and l are two given positive integers and $a_{ij} (1 \leq i \leq k, 1 \leq j \leq l)$ are given positive numbers. Prove that if $q \geq p > 0$, then

$$\left(\sum_{j=1}^l \left(\sum_{i=1}^k a_{ij}^p \right)^{\frac{q}{p}} \right)^{\frac{1}{q}} \leq \left(\sum_{i=1}^k \left(\sum_{j=1}^l a_{ij}^q \right)^{\frac{p}{q}} \right)^{\frac{1}{p}}.$$

M 13. (Kantorovich inequality) Suppose $x_1 < \dots < x_n$ are given positive numbers. Let $\lambda_1, \dots, \lambda_n \geq 0$ and $\lambda_1 + \dots + \lambda_n = 1$. Prove that

$$\left(\sum_{i=1}^n \lambda_i x_i \right) \left(\sum_{i=1}^n \frac{\lambda_i}{x_i} \right) \leq \frac{A^2}{G^2},$$

where $A = \frac{x_1 + x_n}{2}$ and $G = \sqrt{x_1 x_n}$.

M 14. (Czech-Slovak-Polish Match 2001) Let $n \geq 2$ be an integer. Show that

$$(a_1^3 + 1)(a_2^3 + 1) \cdots (a_n^3 + 1) \geq (a_1^2 a_2 + 1)(a_2^2 a_3 + 1) \cdots (a_n^2 a_1 + 1)$$

for all nonnegative reals a_1, \dots, a_n .

M 15. (C1868, De-jun Zhao) Let $n \geq 3$, $a_1 > a_2 > \cdots > a_n > 0$, and $p > q > 0$. Show that

$$a_1^p a_2^q + a_2^p a_3^q + \cdots + a_{n-1}^p a_n^q + a_n^p a_1^q \geq a_1^q a_2^p + a_2^q a_3^p + \cdots + a_{n-1}^q a_n^p + a_n^q a_1^p$$

M 16. (Baltic Way 1996) For which positive real numbers a, b does the inequality

$$x_1 x_2 + x_2 x_3 + \cdots + x_{n-1} x_n + x_n x_1 \geq x_1^a x_2^b x_3^a + x_2^a x_3^b x_4^a + \cdots + x_n^a x_1^b x_2^a$$

holds for all integers $n > 2$ and positive real numbers x_1, \dots, x_n .

M 17. (IMO short List 2000) Let x_1, x_2, \dots, x_n be arbitrary real numbers. Prove the inequality

$$\frac{x_1}{1+x_1^2} + \frac{x_2}{1+x_1^2+x_2^2} + \cdots + \frac{x_n}{1+x_1^2+\cdots+x_n^2} < \sqrt{n}.$$

M 18. (MM²1479, Donald E. Knuth) Let M_n be the maximum value of the quantity

$$\frac{x_n}{(1+x_1+\cdots+x_n)^2} + \frac{x_2}{(1+x_2+\cdots+x_n)^2} + \cdots + \frac{x_1}{(1+x_n)^2}$$

over all nonnegative real numbers (x_1, \dots, x_n) . At what point(s) does the maximum occur? Express M_n in terms of M_{n-1} , and find $\lim_{n \rightarrow \infty} M_n$.

M 19. (IMO 1971) Prove the following assertion is true for $n = 3$ and $n = 5$ and false for every other natural number $n > 2$: if a_1, \dots, a_n are arbitrary real numbers, then

$$\sum_{i=1}^n \prod_{i \neq j} (a_i - a_j) \geq 0.$$

M 20. (IMO 2003) Let $x_1 \leq x_2 \leq \cdots \leq x_n$ be real numbers.

(a) Prove that

$$\left(\sum_{1 \leq i, j \leq n} |x_i - x_j| \right)^2 \leq \frac{2(n^2 - 1)}{3} \sum_{1 \leq i, j \leq n} (x_i - x_j)^2.$$

(b) Show that the equality holds if and only if x_1, x_2, \dots, x_n is an arithmetic sequence.

M 21. (Bulgaria 1995) Let $n \geq 2$ and $0 \leq x_1, \dots, x_n \leq 1$. Show that

$$(x_1 + x_2 + \cdots + x_n) - (x_1 x_2 + x_2 x_3 + \cdots + x_n x_1) \leq \left[\frac{n}{2} \right],$$

and determine when there is equality.

M 22. (MM1407, M. S. Klamkin) Determine the maximum value of the sum

$$x_1^p + x_2^p + \cdots + x_n^p - x_1^q x_2^r - x_2^q x_3^r - \cdots - x_n^q x_1^r,$$

where p, q, r are given numbers with $p \geq q \geq r \geq 0$ and $0 \leq x_i \leq 1$ for all i .

M 23. (IMO Short List 1998) Let a_1, a_2, \dots, a_n be positive real numbers such that

$$a_1 + a_2 + \cdots + a_n < 1.$$

Prove that

$$\frac{a_1 a_2 \cdots a_n (1 - (a_1 + a_2 + \cdots + a_n))}{(a_1 + a_2 + \cdots + a_n)(1 - a_1)(1 - a_2) \cdots (1 - a_n)} \leq \frac{1}{n^{n+1}}.$$

²Mathematics Magazine

M 24. (IMO Short List 1998) Let r_1, r_2, \dots, r_n be real numbers greater than or equal to 1. Prove that

$$\frac{1}{r_1 + 1} + \dots + \frac{1}{r_n + 1} \geq \frac{n}{(r_1 \cdots r_n)^{\frac{1}{n}} + 1}.$$

M 25. (Baltic Way 1991) Prove that, for any real numbers a_1, \dots, a_n ,

$$\sum_{1 \leq i, j \leq n} \frac{a_i a_j}{i + j - 1} \geq 0.$$

M 26. (India 1995) Let x_1, x_2, \dots, x_n be positive real numbers whose sum is 1. Prove that

$$\frac{x_1}{1 - x_1} + \dots + \frac{x_n}{1 - x_n} \geq \sqrt{\frac{n}{n - 1}}.$$

M 27. (Turkey 1997) Given an integer $n \geq 2$, Find the minimal value of

$$\frac{x_1^5}{x_2 + x_3 + \dots + x_n} + \frac{x_2^5}{x_3 + \dots + x_n + x_1} + \dots + \frac{x_n^5}{x_1 + x_3 + \dots + x_{n-1}}$$

for positive real numbers x_1, \dots, x_n subject to the condition $x_1^2 + \dots + x_n^2 = 1$.

M 28. (China 1996) Suppose $n \in \mathbf{N}$, $x_0 = 0$, $x_1, \dots, x_n > 0$, and $x_1 + \dots + x_n = 1$. Prove that

$$1 \leq \sum_{i=1}^n \frac{x_i}{\sqrt{1 + x_0 + \dots + x_{i-1}} \sqrt{x_i + \dots + x_n}} < \frac{\pi}{2}$$

M 29. (Vietnam 1998) Let x_1, \dots, x_n be positive real numbers satisfying

$$\frac{1}{x_1 + 1998} + \dots + \frac{1}{x_n + 1998} = \frac{1}{1998}.$$

Prove that

$$\frac{(x_1 \cdots x_n)^{\frac{1}{n}}}{n - 1} \geq 1998$$

M 30. (C2768 Mohammed Aassila) Let x_1, \dots, x_n be n positive real numbers. Prove that

$$\frac{x_1}{\sqrt{x_1 x_2 + x_2^2}} + \frac{x_2}{\sqrt{x_2 x_3 + x_3^2}} + \dots + \frac{x_n}{\sqrt{x_n x_1 + x_1^2}} \geq \frac{n}{\sqrt{2}}$$

M 31. (C2842, George Tsintsifas) Let x_1, \dots, x_n be positive real numbers. Prove that

$$(a) \frac{x_1^n + \dots + x_n^n}{n x_1 \cdots x_n} + \frac{n (x_1 \cdots x_n)^{\frac{1}{n}}}{x_1 + \dots + x_n} \geq 2,$$

$$(b) \frac{x_1^n + \dots + x_n^n}{x_1 \cdots x_n} + \frac{(x_1 \cdots x_n)^{\frac{1}{n}}}{x_1 + \dots + x_n} \geq 1.$$

M 32. (C2423, Walther Janous) Let $x_1, \dots, x_n (n \geq 2)$ be positive real numbers such that $x_1 + \dots + x_n = 1$. Prove that

$$\left(1 + \frac{1}{x_1}\right) \cdots \left(1 + \frac{1}{x_n}\right) \geq \left(\frac{n - x_1}{1 - x_1}\right) \cdots \left(\frac{n - x_n}{1 - x_n}\right)$$

Determine the cases of equality.

M 33. (C1851, Walther Janous) Let $x_1, \dots, x_n (n \geq 2)$ be positive real numbers such that

$$x_1^2 + \dots + x_n^2 = 1.$$

Prove that

$$\frac{2\sqrt{n} - 1}{5\sqrt{n} - 1} \leq \sum_{i=1}^n \frac{2 + x_i}{5 + x_i} \leq \frac{2\sqrt{n} + 1}{5\sqrt{n} + 1}.$$

M 34. (C1429, D. S. Mitirinovic, J. E. Pecaric) Show that

$$\sum_{i=1}^n \frac{x_i}{x_i^2 + x_{i+1}x_{i+2}} \leq n - 1$$

where x_1, \dots, x_n are $n \geq 3$ positive real numbers. Of course, $x_{n+1} = x_1, x_{n+2} = x_2$. ³

M 35. (Belarus 1998 S. Sobolevski) Let $a_1 \leq a_2 \leq \dots \leq a_n$ be positive real numbers. Prove the inequalities

$$(a) \frac{n}{\frac{1}{a_1} + \dots + \frac{1}{a_n}} \geq \frac{a_1}{a_n} \cdot \frac{a_1 + \dots + a_n}{n},$$

$$(b) \frac{n}{\frac{1}{a_1} + \dots + \frac{1}{a_n}} \geq \frac{2k}{1+k^2} \cdot \frac{a_1 + \dots + a_n}{n},$$

where $k = \frac{a_n}{a_1}$.

M 36. (Hong Kong 2000) Let $a_1 \leq a_2 \leq \dots \leq a_n$ be n real numbers such that

$$a_1 + a_2 + \dots + a_n = 0.$$

Show that

$$a_1^2 + a_2^2 + \dots + a_n^2 + na_1a_n \leq 0.$$

M 37. (Poland 2001) Let $n \geq 2$ be an integer. Show that

$$\sum_{i=1}^n x_i^i + \binom{n}{2} \geq \sum_{i=1}^n ix_i$$

for all nonnegative reals x_1, \dots, x_n .

M 38. (Korea 1997) Let a_1, \dots, a_n be positive numbers, and define

$$A = \frac{a_1 + \dots + a_n}{n}, G = (a_1 \cdots a_n)^{\frac{1}{n}}, H = \frac{n}{\frac{1}{a_1} + \dots + \frac{1}{a_n}}$$

(a) If n is even, show that

$$\frac{A}{H} \leq -1 + 2 \left(\frac{A}{G} \right)^n.$$

(b) If n is odd, show that

$$\frac{A}{H} \leq -\frac{n-2}{n} + \frac{2(n-1)}{n} \left(\frac{A}{G} \right)^n.$$

M 39. (Romania 1996) Let x_1, \dots, x_n, x_{n+1} be positive reals such that

$$x_{n+1} = x_1 + \dots + x_n.$$

Prove that

$$\sum_{i=1}^n \sqrt{x_i(x_{n+1} - x_i)} \leq \sqrt{x_{n+1}(x_{n+1} - x_i)}$$

M 40. (C2730, Peter Y. Woo) Let $AM(x_1, \dots, x_n)$ and $GM(x_1, \dots, x_n)$ denote the arithmetic mean and the geometric mean of the positive real numbers x_1, \dots, x_n respectively. Given positive real numbers $a_1, \dots, a_n, b_1, \dots, b_n$, (a) prove that

$$GM(a_1 + b_1, \dots, a_n + b_n) \geq GM(a_1, \dots, a_n) + GM(b_1, \dots, b_n).$$

For each real number $t \geq 0$, define

$$f(t) = GM(t + b_1, t + b_2, \dots, t + b_n) - t$$

(b) Prove that f is a monotonic increasing function, and that

$$\lim_{t \rightarrow \infty} f(t) = AM(b_1, \dots, b_n)$$

³Original version is to show that $\sup \sum_{i=1}^n \frac{x_i}{x_i^2 + x_{i+1}x_{i+2}} = n - 1$.

M 41. (C1578, O. Johnson, C. S. Goodlad) For each fixed positive real number a_n , maximize

$$\frac{a_1 a_2 \cdots a_n}{(1 + a_1)(a_1 + a_2)(a_2 + a_3) \cdots (a_{n-1} + a_n)}$$

over all positive real numbers a_1, \dots, a_{n-1} .

M 42. (C1630, Isao Ashiba) Maximize

$$a_1 a_2 + a_3 a_4 + \cdots + a_{2n-1} a_{2n}$$

over all permutations a_1, \dots, a_{2n} of the set $\{1, 2, \dots, 2n\}$

M 43. (C1662, M. S. Klamkin) Prove that

$$\frac{x_1^{2r+1}}{s - x_1} + \frac{x_2^{2r+1}}{s - x_2} + \cdots + \frac{x_n^{2r+1}}{s - x_n} \geq \frac{4^r}{(n-1)n^{2r-1}} (x_1 x_2 + x_2 x_3 + \cdots + x_n x_1)^r$$

where $n > 3$, $r \geq \frac{1}{2}$, $x_i \geq 0$ for all i , and $s = x_1 + \cdots + x_n$. Also, Find some values of n and r such that the inequality is sharp.

M 44. (C1674, M. S. Klamkin) Given positive real numbers r, s and an integer $n > \frac{r}{s}$, find positive real numbers x_1, \dots, x_n so as to minimize

$$\left(\frac{1}{x_1^r} + \frac{1}{x_2^r} + \cdots + \frac{1}{x_n^r} \right) (1 + x_1)^s (1 + x_2)^s \cdots (1 + x_n)^s.$$

M 45. (C1691, Walther Janous) Let $n \geq 2$. Determine the best upper bound of

$$\frac{x_1}{x_2 x_3 \cdots x_n + 1} + \frac{x_2}{x_1 x_3 \cdots x_n + 1} + \cdots + \frac{x_n}{x_1 x_2 \cdots x_{n-1} + 1}$$

over all $x_1, \dots, x_n \in [0, 1]$.

M 46. (C1892, Marcin E. Kuczma) Let $n \geq 4$ be an integer. Find the exact upper and lower bounds for the cyclic sum

$$\sum_{i=1}^n \frac{x_i}{x_{i-1} + x_i + x_{i+1}}$$

over all n -tuples of nonnegative numbers x_1, \dots, x_n such that $x_{i-1} + x_i + x_{i+1} > 0$ for all i . Of course, $x_{n+1} = x_1$, $x_0 = x_n$. Characterize all cases in which either one of these bounds is attained.

M 47. (C1953, M. S. Klamkin) Determine a necessary and sufficient condition on real constants r_1, \dots, r_n such that

$$x_1^2 + x_2^2 + \cdots + x_n^2 \geq (r_1 x_1 + r_2 x_2 + \cdots + r_n x_n)^2$$

holds for all real numbers x_1, \dots, x_n .

M 48. (C2018, Marcin E. Kuczma) How many permutations (x_1, \dots, x_n) of $\{1, 2, \dots, n\}$ are there such that the cyclic sum

$$|x_1 - x_2| + |x_2 - x_3| + \cdots + |x_{n-1} - x_n| + |x_n - x_1|$$

is (a) a minimum, (b) a maximum?

M 49. (C2214, Walther Janous) Let $n \geq 2$ be a natural number. Show that there exists a constant $C = C(n)$ such that for all $x_1, \dots, x_n \geq 0$ we have

$$\sum_{i=1}^n \sqrt{x_i} \leq \sqrt{\prod_{i=1}^n (x_i + C)}$$

Determine the minimum $C(n)$ for some values of n . (For example, $C(2) = 1$.)

M 50. (C2615, M. S. Klamkin) Suppose that x_1, \dots, x_n are non-negative numbers such that

$$\sum x_i^2 \sum (x_i x_{i+1})^2 = \frac{n(n+1)}{2}$$

where the sums here and subsequently are symmetric over the subscripts $\{1, \dots, n\}$. (a) Determine the maximum of $\sum x_i$. (b) Prove or disprove that the minimum of $\sum x_i$ is $\sqrt{\frac{n(n+1)}{2}}$.

M 51. (Turkey 1996) Given real numbers $0 = x_1 < x_2 < \dots < x_{2n}, x_{2n+1} = 1$ with $x_{i+1} - x_i \leq h$ for $1 \leq i \leq n$, show that

$$\frac{1-h}{2} < \sum_{i=1}^n x_{2i}(x_{2i+1} - x_{2i-1}) < \frac{1+h}{2}.$$

M 52. (Poland 2002) Prove that for every integer $n \geq 3$ and every sequence of positive numbers x_1, \dots, x_n at least one of the two inequalities is satisfied :

$$\sum_{i=1}^n \frac{x_i}{x_{i+1} + x_{i+2}} \geq \frac{n}{2}, \quad \sum_{i=1}^n \frac{x_i}{x_{i-1} + x_{i-2}} \geq \frac{n}{2}.$$

Here, $x_{n+1} = x_1, x_{n+2} = x_2, x_0 = x_n, x_{-1} = x_{n-1}$.

M 53. (China 1997) Let x_1, \dots, x_{1997} be real numbers satisfying the following conditions:

$$-\frac{1}{\sqrt{3}} \leq x_1, \dots, x_{1997} \leq \sqrt{3}, x_1 + \dots + x_{1997} = -318\sqrt{3}$$

Determine the maximum value of $x_1^{12} + \dots + x_{1997}^{12}$.

M 54. (C2673, George Baloglu) Let $n > 1$ be an integer. (a) Show that

$$(1 + a_1 \cdots a_n)^n \geq a_1 \cdots a_n (1 + a_1^{n-2}) \cdots (1 + a_1^{n-2})$$

for all $a_1, \dots, a_n \in [1, \infty)$ if and only if $n \geq 4$.

(b) Show that

$$\frac{1}{a_1(1 + a_2^{n-2})} + \frac{1}{a_2(1 + a_3^{n-2})} + \cdots + \frac{1}{a_n(1 + a_1^{n-2})} \geq \frac{n}{1 + a_1 \cdots a_n}$$

for all $a_1, \dots, a_n > 0$ if and only if $n \leq 3$.

(c) Show that

$$\frac{1}{a_1(1 + a_1^{n-2})} + \frac{1}{a_2(1 + a_2^{n-2})} + \cdots + \frac{1}{a_n(1 + a_n^{n-2})} \geq \frac{n}{1 + a_1 \cdots a_n}$$

for all $a_1, \dots, a_n > 0$ if and only if $n \leq 8$.

M 55. (C2557, Gord Sinnamon, Hans Heinig) (a) Show that for all positive sequences $\{x_i\}$

$$\sum_{k=1}^n \sum_{j=1}^k \sum_{i=1}^j x_i \leq 2 \sum_{k=1}^n \left(\sum_{j=1}^k x_j \right)^2 \frac{1}{x_k}.$$

(b) Does the above inequality remain true without the factor 2? (c) What is the minimum constant c that can replace the factor 2 in the above inequality?

M 56. (C1472, Walther Janous) For each integer $n \geq 2$, Find the largest constant C_n such that

$$C_n \sum_{i=1}^n |a_i| \leq \sum_{1 \leq i < j \leq n} |a_i - a_j|$$

for all real numbers a_1, \dots, a_n satisfying $\sum_{i=1}^n a_i = 0$.

M 57. (China 2002) Given $c \in (\frac{1}{2}, 1)$. Find the smallest constant M such that, for any integer $n \geq 2$ and real numbers $1 < a_1 \leq a_2 \leq \dots \leq a_n$, if

$$\frac{1}{n} \sum_{k=1}^n k a_k \leq c \sum_{k=1}^n a_k,$$

then

$$\sum_{k=1}^n a_k \leq M \sum_{k=1}^m k a_k,$$

where m is the largest integer not greater than cn .

M 58. (Serbia 1998) Let x_1, x_2, \dots, x_n be positive numbers such that

$$x_1 + x_2 + \dots + x_n = 1.$$

Prove the inequality

$$\frac{a^{x_1-x_2}}{x_1+x_2} + \frac{a^{x_2-x_3}}{x_2+x_3} + \dots + \frac{a^{x_n-x_1}}{x_n+x_1} \geq \frac{n^2}{2},$$

holds true for every positive real number a . Determine also when the equality holds.

M 59. (MM1488, Heinz-Jurgen Seiffert) Let n be a positive integer. Show that if $0 < x_1 \leq x_2 \leq \dots \leq x_n$, then

$$\prod_{i=1}^n (1+x_i) \left(\sum_{j=0}^n \prod_{k=1}^j \frac{1}{x_k} \right) \geq 2^n (n+1)$$

with equality if and only if $x_1 = \dots = x_n = 1$.

M 60. (Leningrad Mathematical Olympiads 1968) Let a_1, a_2, \dots, a_p be real numbers. Let $M = \max S$ and $m = \min S$. Show that

$$(p-1)(M-m) \leq \sum_{1 \leq i, j \leq n} |a_i - a_j| \leq \frac{p^2}{4}(M-m)$$

M 61. (Leningrad Mathematical Olympiads 1973) Establish the following inequality

$$\sum_{i=0}^8 2^i \cos\left(\frac{\pi}{2^{i+2}}\right) \left(1 - \cos\left(\frac{\pi}{2^{i+2}}\right)\right) < \frac{1}{2}.$$

M 62. (Leningrad Mathematical Olympiads 2000) Show that, for all $0 < x_1 \leq x_2 \leq \dots \leq x_n$,

$$\frac{x_1 x_2}{x_3} + \frac{x_2 x_3}{x_4} + \dots + \frac{x_{n_1} x_1}{x_2} + \frac{x_n x_1}{x_2} \geq \sum_{i=1}^n x_i$$

M 63. (Mongolia 1996) Show that, for all $0 < a_1 \leq a_2 \leq \dots \leq a_n$,

$$\left(\frac{a_1+a_2}{2}\right) \left(\frac{a_2+a_3}{2}\right) \dots \left(\frac{a_n+a_1}{2}\right) \leq \left(\frac{a_1+a_2+a_3}{3}\right) \left(\frac{a_2+a_3+a_4}{3}\right) \dots \left(\frac{a_n+a_1+a_2}{3}\right).$$

5.2 Problems for Putnam Seminar

P 1. [Putnam 04A6] Suppose that $f(x, y)$ is a continuous real-valued function on the unit square $0 \leq x \leq 1, 0 \leq y \leq 1$. Show that

$$\begin{aligned} & \int_0^1 \left(\int_0^1 f(x, y) dx \right)^2 dy + \int_0^1 \left(\int_0^1 f(x, y) dy \right)^2 dx \\ & \leq \left(\int_0^1 \int_0^1 f(x, y) dx dy \right)^2 + \int_0^1 \int_0^1 (f(x, y))^2 dx dy. \end{aligned}$$

P 2. [Putnam 04B2] Let m and n be positive integers. Show that

$$\frac{(m+n)!}{(m+n)^{m+n}} < \frac{m!}{m^m} \frac{n!}{n^n}.$$

P 3. [Putnam 03A2] Let a_1, a_2, \dots, a_n and b_1, b_2, \dots, b_n be nonnegative real numbers. Show that

$$(a_1 a_2 \cdots a_n)^{1/n} + (b_1 b_2 \cdots b_n)^{1/n} \leq [(a_1 + b_1)(a_2 + b_2) \cdots (a_n + b_n)]^{1/n}.$$

P 4. [Putnam 03A3] Find the minimum value of

$$|\sin x + \cos x + \tan x + \cot x + \sec x + \csc x|$$

for real numbers x .

P 5. [Putnam 03A4] Suppose that a, b, c, A, B, C are real numbers, $a \neq 0$ and $A \neq 0$, such that

$$|ax^2 + bx + c| \leq |Ax^2 + Bx + C|$$

for all real numbers x . Show that

$$|b^2 - 4ac| \leq |B^2 - 4AC|.$$

P 6. [Putnam 03B6] Let $f(x)$ be a continuous real-valued function defined on the interval $[0, 1]$. Show that

$$\int_0^1 \int_0^1 |f(x) + f(y)| dx dy \geq \int_0^1 |f(x)| dx.$$

P 7. [Putnam 02B3] Show that, for all integers $n > 1$,

$$\frac{1}{2ne} < \frac{1}{e} - \left(1 - \frac{1}{n}\right)^n < \frac{1}{ne}.$$

P 8. [Putnam 01A6] Can an arc of a parabola inside a circle of radius 1 have a length greater than 4?

P 9. [Putnam 99A5] Prove that there is a constant C such that, if $p(x)$ is a polynomial of degree 1999, then

$$|p(0)| \leq C \int_{-1}^1 |p(x)| dx.$$

P 10. [Putnam 99B4] Let f be a real function with a continuous third derivative such that $f(x), f'(x), f''(x), f'''(x)$ are positive for all x . Suppose that $f'''(x) \leq f(x)$ for all x . Show that $f'(x) < 2f(x)$ for all x .

P 11. [Putnam 98B4] Let $a_{m,n}$ denote the coefficient of x^n in the expansion of $(1 + x + x^2)^m$. Prove that for all integers $k \geq 0$,

$$0 \leq \sum_{i=0}^{\lfloor \frac{2k}{3} \rfloor} (-1)^i a_{k-i,i} \leq 1.$$

P 12. [Putnam 98B1] Find the minimum value of

$$\frac{(x + \frac{1}{x})^6 - (x^6 + \frac{1}{x^6}) - 2}{(x + \frac{1}{x})^3 + (x^3 + \frac{1}{x^3})}$$

for $x > 0$.

P 13. [Putnam 96B2] Show that for every positive integer n ,

$$\left(\frac{2n-1}{e}\right)^{\frac{2n-1}{2}} < 1 \cdot 3 \cdot 5 \cdots (2n-1) < \left(\frac{2n+1}{e}\right)^{\frac{2n+1}{2}}.$$

P 14. [Putnam 96B3] Given that $\{x_1, x_2, \dots, x_n\} = \{1, 2, \dots, n\}$, find, with proof, the largest possible value, as a function of n (with $n \geq 2$), of

$$x_1x_2 + x_2x_3 + \cdots + x_{n-1}x_n + x_nx_1.$$

P 15. [Putnam 91B6] Let a and b be positive numbers. Find the largest number c , in terms of a and b , such that

$$a^x b^{1-x} \leq a \frac{\sinh ux}{\sinh u} + b \frac{\sinh u(1-x)}{\sinh u}$$

for all u with $0 < |u| \leq c$ and for all x , $0 < x < 1$.

P 16. (CMJ⁴416, Joanne Harris) For what real values of c is

$$\frac{e^x + e^{-x}}{2} \leq e^{cx^2}.$$

for all real x ?

P 17. (CMJ420, Edward T. H. Wang) It is known [Daniel I. A. Cohen, *Basic Techniques of Combinatorial Theory*, p.56] and easy to show that $2^n < \binom{2n}{n} < 2^{2n}$ for all integers $n > 1$. Prove that the stronger inequalities

$$\frac{2^{2n-1}}{\sqrt{n}} < \binom{2n}{n} < \frac{2^{2n}}{\sqrt{n}}$$

hold for all $n \geq 4$.

P 18. (CMJ379, Mohammad K. Azarian) Let x be any real number. Prove that

$$(1 - \cos x) \left| \sum_{k=1}^n \sin(kx) \right| \left| \sum_{k=1}^n \cos(kx) \right| \leq 2.$$

P 19. (CMJ392 Robert Jones) Prove that

$$\left(1 + \frac{1}{x^2}\right) \left(x \sin \frac{1}{x}\right) > 1 \text{ for } x \geq \frac{1}{\sqrt{5}}.$$

P 20. (CMJ431 R. S. Luthar) Let $0 < \phi < \theta < \frac{\pi}{2}$. Prove that

$$[(1 + \tan^2 \phi)(1 + \sin^2 \phi)]^{\csc^2 \phi} < [(1 + \tan^2 \theta)(1 + \sin^2 \theta)]^{\csc^2 \theta}.$$

P 21. (CMJ451, Mohammad K. Azarian) Prove that

$$\pi^{\sec^2 \alpha} \cos^2 \alpha + \pi^{\csc^2 \alpha} \sin^2 \alpha \geq \pi^2,$$

provided $0 < \alpha < \frac{\pi}{2}$.

⁴The College Mathematics Journal

P 22. (CMJ446, Norman Schaumberger) If x , y , and z are the radian measures of the angles in a (non-degenerate) triangle, prove that

$$\pi \sin \frac{3}{\pi} \geq x \sin \frac{1}{x} + y \sin \frac{1}{y} + z \sin \frac{1}{z}.$$

P 23. (CMJ461, Alex Necochea) Let $0 < x < \frac{\pi}{2}$ and $0 < y < 1$. Prove that

$$x - \arcsin y \leq \frac{\sqrt{1 - y^2 - \cos x}}{y},$$

with equality holding if and only if $y = \sin x$.

P 24. (CMJ485 Norman Schaumberger) Prove that

- (1) if $a \geq b > 1$ or $1 > a \geq b > 0$, then $a^{b^b} b^{a^a} \geq a^{b^a} b^{a^b}$; and
- (2) if $a > 1 > b > 0$, then $a^{b^b} b^{a^a} \leq a^{b^a} b^{a^b}$.

P 25. (CMJ524 Norman Schaumberger) Let a , b , and c be positive real numbers. Show that

$$a^a b^b c^c \geq \left(\frac{a+b}{2}\right)^a \left(\frac{b+c}{2}\right)^b \left(\frac{c+a}{2}\right)^c \geq b^a c^b a^c.$$

P 26. (CMJ567 H.-J. Seiffert) Show that for all distinct positive real numbers x and y ,

$$\left(\frac{\sqrt{x} + \sqrt{y}}{2}\right)^2 < \frac{x - y}{2 \sinh \frac{x-y}{x+y}} < \frac{x + y}{2}.$$

P 27. (CMJ572, George Baloglou and Robert Underwood) Prove or disprove that for $\theta \in (-\frac{\pi}{4}, \frac{\pi}{4})$, $\cosh \theta \leq \frac{1}{\sqrt{1 - \tan^2 \theta}}$.

P 28. (CMJ603, Juan-Bosco Romero Marquez) Let a and b be distinct positive real numbers and let n be a positive integer. Prove that

$$\frac{a+b}{2} \leq \sqrt[n]{\frac{b^{n+1} - a^{n+1}}{(n+1)(b-a)}} \leq \sqrt[n]{\frac{a^n + b^n}{2}}.$$

P 29. (MM⁵904, Norman Schaumberger) For $x > 2$, prove that

$$\ln \left(\frac{x}{x-1} \right) \leq \sum_{j=0}^{\infty} \frac{1}{x^{2j}} \leq \ln \left(\frac{x-1}{x-2} \right).$$

P 30. (MM1590, Constantin P. Niculescu) For given a , $0 < a < \frac{\pi}{2}$, determine the minimum value of $\alpha \geq 0$ and the maximum value of $\beta \geq 0$ for which

$$\left(\frac{x}{a}\right)^\alpha \leq \frac{\sin x}{\sin a} \leq \left(\frac{x}{a}\right)^\beta.$$

(This generalizes the well-known inequality due to Jordan, which asserts that $\frac{2x}{\pi} \leq \sin x \leq 1$ on $[0, \frac{\pi}{2}]$.)

P 31. (MM1597, Constantin P. Niculescu) For every $x, y \in (0, \sqrt{\frac{\pi}{2}})$ with $x \neq y$, prove that

$$\left(\ln \frac{1 - \sin xy}{1 + \sin xy} \right)^2 \geq \ln \frac{1 - \sin x^2}{1 + \sin x^2} \ln \frac{1 - \sin y^2}{1 + \sin y^2}.$$

P 32. (MM1599, Ice B. Risteski) Given $\alpha > \beta > 0$ and $f(x) = x^\alpha (1-x)^\beta$. If $0 < a < b < 1$ and $f(a) = f(b)$, show that $f'(\alpha) < -f'(\beta)$.

⁵Mathematics Magazine

P 33. (MM Q197, Norman Schaumberger) Prove that if $b > a > 0$, then $\left(\frac{a}{b}\right)^a \geq \frac{e^a}{e^b} \geq \left(\frac{a}{b}\right)^b$.

P 34. (MM1618, Michael Golomb) Prove that $0 < x < \pi$,

$$x \frac{\pi - x}{\pi + x} < \sin x < \left(3 - \frac{x}{\pi}\right) x \frac{\pi - x}{\pi + x}.$$

P 35. (MM1634, Constantin P. Niculescu) Find the smallest constant $k > 0$ such that

$$\frac{ab}{a + b + 2c} + \frac{bc}{b + c + 2a} + \frac{ca}{c + a + 2b} \leq k(a + b + c)$$

for every $a, b, c > 0$.

P 36. (MM1233, Robert E. Shafer) Prove that if $x > -1$ and $x \neq 0$, then

$$\frac{x^2}{1 + x + \frac{x^2}{2} - \frac{\frac{x^4}{120}}{1+x+\frac{31}{252}x^2}} < [\ln(1 + x)]^2 < \frac{x^2}{1 + x + \frac{x^2}{2} - \frac{\frac{x^4}{240}}{1+x+\frac{1}{20}x^2}}.$$

P 37. (MM1236, Mihaly Bencze) Let the functions f and g be defined by

$$f(x) = \frac{\pi^2 x}{2\pi^2 + 8x^2} \text{ and } g(x) = \frac{8x}{4\pi^2 + \pi x^2}$$

for all real x . Prove that if A , B , and C are the angles of an acuted-angle triangle, and R is its circumradius then

$$f(A) + f(B) + f(C) < \frac{a + b + c}{4R} < g(A) + g(B) + g(C).$$

P 38. (MM1245, Fouad Nakhli) For each number x in open interval $(1, e)$ it is easy to show that there is a unique number y in (e, ∞) such that $\frac{\ln y}{y} = \frac{\ln x}{x}$. For such an x and y , show that $x + y > x \ln y + y \ln x$.

P 39. (MM Q725, S. Kung) Show that $(\sin x)y \leq \sin(xy)$, where $0 < x < \pi$ and $0 < y < 1$.

P 40. (MM Q771, Norman Schaumberger) Show that if $0 < \theta < \frac{\pi}{2}$, then $\sin 2\theta \geq (\tan \theta)^{\cos 2\theta}$.

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